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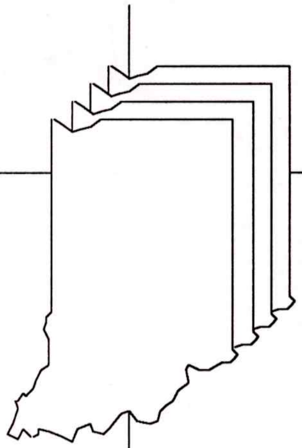

State of Indiana

GEOGRAPHIC INFORMATION SYSTEM CONFERENCE

Proceedings

University GIS Alliance

Ball State University
Indiana State University
Indiana University
I.U.P.U.I.
Purdue University

November 15-16, 1990

Foreword

This Proceedings is the result of the Second Annual State of Indiana Geographic Information Systems Conference. The Conference was held on November 15-16, 1990. No Proceedings were published from the First GIS Conference.

The State GIS Conferences were the result of the joint efforts of the University GIS Alliance. This unique group made up of representatives from Ball State University at Muncie, Indiana State University at Terre Haute, Indiana University at Bloomington, I.U.P.U.I. at Indianapolis and Purdue University at West Lafayette, Indiana was organized in 1989.

The purposes of Alliance are to:

- Provide leadership in development of GIS technology and promote its capabilities within the State of Indiana.
- Establish a formal network of individuals and resources at various Indiana universities who are involved in GIS technologies.
- Provide the leading edge for GIS technology development.
- Develop an environment for cooperative GIS research including data and information sharing.
- Organize educational opportunities such as training, symposia, conferences and workshops.

We appreciate the cooperation of the Alliance members in organizing and conducting the Conference. Much effort went into this conference, especially by students who often receive little recognition. These proceedings are meant to provide further educational value as a good library resource. The Alliance members look forward to hearing from you and knowing how we might assist in fulfilling our purposes.

Paul Mausel, Conference Chair
Indiana State University

Chris J. Johannsen, Co-Chair
Purdue University

TABLE OF CONTENTS

PLENARY SESSION

SESSION 1B: GIS TOOLS FOR ENVIRONMENTAL MANAGEMENT SESSION

SESSION 2A: INFRASTRUCTURE: PROBLEMS AND GIS/AM/FM SOLUTIONS SESSION

SESSION 2B: LAND INFORMATION SYSTEMS (LIS): NATURE AND APPLICATIONS SESSION

POSTER SESSION

VOLUNTARY PAPER SESSION

LOCAL, COUNTY, AND STATE APPLICATIONS OF GIS

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Government organizations are proceeding and planning to implement GIS in rapidly growing numbers. As organizations pursue their GIS objectives, the ways in which GIS is used continue to expand. And while organizations become more advanced in their application of GIS, the GIS industry also grows to meet the challenges faced by those organizations. This discussion will review traditional GIS applications in municipal, county and state government, discuss newly emerging application areas, and present technological advancements which are occurring in the GIS industry to address the requirements of these new uses in operational environments.

Geographic Information Systems and Remote Sensing: The Interface at Global Scales[1].

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Abstract

Geographic Information systems and remote sensing seem an ideal match. The former technology is directed toward the storage and analysis of geographic data and the latter technology is designed to collected geographic data. To date, the union of this technologies has been less successful that anticipated. The factors which currently limit progress in this union become particularly evident in efforts to compile global-scale descriptions of the Earth, as is needed to carry out NASA Earth System Science and IGBP Global Change global-scale studies . The difficulties encountered originate less within the inherent capabilities of the technologies than in the alternate conceptual models of geographic data that have dominated the evolution in each field. In addition, the analytical underpinnings of both data systems - cartographic representation of the Earth's surface - has generally not received the attention needed to effectively interface these disparate data models. The long-term success of computer-based geographic research is highly dependent on resolution of these current difficulties.

Introduction

Execution of global-scale studies, as envisaged in the National Aeronautic and Space Administration's Earth Systems Science initiative and International Geosphere-Biosphere Program "Global Change" activities, is premised on the evolving technologies of information processing in computer-based geographic information systems and information gathering with satellite- and aircraft-based remote sensing systems (National Research Council 1986; National Aeronautics and Space Administration 1988). Recent successes in operating coarse resolution, general circulation models of the Earth's climate on digital computers and the spectacular series of Earth images reporting phenomena such as green leaf density, surface temperature, cloud climatology and planetary ozone distribution, have encouraged many researchers to believe that it is now time to re-address the global dynamics of life processes and related systems on this planet (Washington and Parkinson 1986; Rasool 1987).

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[1] This narrative is abstracted from a broader discussion to be published shortly in J. R. Mather and G. V. Sdasyuk (eds.) *Global Change: Geographic Approaches*, University of Arizona Press and in Russian by Progress Publishers, Moscow.

At first glance GIS and remote sensing appear to be an ideal solution to this problem of improving knowledge of Earth processes and dynamics. Geographic information systems are intended to automate storage and processing of terrestrial data and remote sensing is directed toward collection of geographic observations (Marble and Peuquet 1985; Mounsey and Tomlinson 1988). The current reality is that these technologies are in an early stage of development. Both geographic information systems and remote sensing technologies will need to be advanced beyond their current status if the goals of global-scale research are to be achieved. In particular, discrepancies between the capacity of geographic information systems to handle the information structure of remote sensed data and the capability of remotely sensed data to provide information compatible with data gathered by more traditional means requires considerable attention.

Problems.

The fundamental problems that are encountered in combining GIS and remote sensing technologies occur at the interface between computer science, cartography, remote sensing and geography. Questions concerning data structures, integration, mapping, and integrated analysis must be resolved before GIS and remote sensing may be considered compatible. Efforts to "place blame" on either technologies or their practioners is an exercise in futility. The "fault", if there is any, lies in tremendous impact these technologies have had on technical methods and scientific understanding employed in geographic analysis. The difficulties in combining these technologies occur because our models of data and information are being altered by the technologies. Understanding and resolution of the current conflicts can only occur when an appreciation of these changing perceptions is accomplished.

Contemporary Terrestrial Remote Sensing

Remote sensing has been in the midst of a revolution over the last twenty five years. New sensors, satellite platforms and computer-based numerical image analysis have caused fundamental changes in image-based interpretation of the Earth. The complex of multispectral observations from the solar reflective, terrestrial emissive as well as a variety of artificial (self-generated) electromagnetic radiation sources (ignoring geomagnetic and acoustical sources) have produced an analysis problem that is several orders of magnitude more complex than interpretation of a simple panchromatic aerial photograph. To overcome these difficulties, substantial emphasis has been given to the development of computer-based image analysis systems.

Pattern Recognition and Land Cover Analysis

Considerable attention has been given to statistical pattern recognition, as a means of extracting land cover classes from numerical image data. (Anderson et al. 1976; Swain and Davis 1978; Jensen 1986). This "signature" model is still widely employed and provides a potentially powerful means to extract nominal information (land cover) from the data - particularly if the spectral structure of radiant exitance from the landscape, as a function of land cover, is known apriori. However, pattern recognition has often met with limited success because, in individual images, many differing land cover types, (e.g. forest and corn, soils and urban, water and shadow) often produce the same spectral pattern (Todd et al. 1973; Fitzpatrick-Lins 1978; Gaydos and Newland 1978; Jayroe 1978; Jensen 1981).

Accurate, reliable extraction of land cover information from numerical remotely sensed data remains today as much an art as a science. Use of the time domain, broadening the spectral coverage of observations and active incorporation of ancillary information in the classification processes should significantly improve the reliability of this type of information extraction from remotely sensed data (Tucker et al. 1985; Hall and Badwar 1987; Crist and Kauth 1986). If nominal land cover analysis is a primary objective for remote sensing data analysis considerable further research will be needed to establish consistent, reliable means to accomplish this task (Williams et al. 1984; Wharton 1987)

Biophysical Remote Sensing

Efforts to improve the reliability of land cover mapping through computer processed remotely sensed data have revealed limited understanding of geographic variability and temporal dynamics of radiatively active landscape elements - the surface materials that reflect and emit radiation. A new focus in terrestrial remote sensing research has been stimulated by this problem; biophysical remote sensing (Malila and Wagner 1972; Goward and Oliver 1977; Jensen 1983; Justice et al. 1985; Brest and Goward 1987; Strahler et al. 1986; Goward 1989). The primary distinguishing feature of this approach to remotely sensed data analysis is that land cover attributes such as albedo, percentage green foliage and soil moisture, are extracted directly from the measurements without intervening land cover classification. The advent of computer processing and advanced sensor systems has significantly advanced this aspect of terrestrial remote sensing.

An apparent limitation of remote sensing, at least within land cover analysis, has been converted to a major strength in biophysical remote sensing. The difficulties encountered in interpreting land cover from visible and near infrared observations (e.g. Landsat MSS and AVHRR observations) occurs because only green foliage, water and other (e.g. soil, concrete asphalt, etc.) may be spectrally distinguished in these data. However this limited generality in landscape spectral diversity produces a general measure of landscape "greenness" which is a vitally important environmental indicator (e.g., photosynthetic capacity of the landscape) (Justice et al. 1985; Goward et al. 1985; Tucker and Sellers 1986; Fung et al. 1987; Johnson et al. 1987; Goward and Hope 1989)

This shift toward biophysical remote sensing has produced a new class of geographic data which consists of contiguous but discrete measurements -

often referred to as "raster" data structure in GIS terminology. These measurements can neither be contoured (isoline) nor classified (choropleth) without a loss of information and precision. This is because discrete land cover conditions can and do exist in close proximity over long periods of time. Preservation of the radiometric and spatial integrity of the original measurements, as well as derived parameters, is critically important to evaluating landscape state and dynamics using biophysical remote sensing. The basic data system requirements for combining biophysical remote sensing data sets with ancillary (e.g., GIS map-type) information has not, as of yet, been given much attention outside the remote sensing community.

Computer-Based Geographic Information Systems

The concept of a geographic information system, at its simplest, is as a means store and easily retrieve geographic data. A well organized map cabinet is a good example of a simple GIS and some of the early work in automated cartography and computer-based GIS were not far removed from the concept of an electronic map case (Tomlinson 1972). A more sophisticated GIS allows cross-referencing between maps, compilation of new maps from composite information and comparison with non-map (e.g. remotely sensed) data (Bryant and Zobrist 1976). The most sophisticated GIS operations currently being considered would have the capacity to integrate the available information conduct deductive logic and make predictions based on data structure and and theory (Smith et al. 1987).

The Vector-Raster "Problem"

Much of research, to date, on geographic information systems has focussed on local to regional scales and concentrated on vector data structures (Marble and Peuquet 1985; Merchant and Ripple 1987; Merchant 1988). This concentration represents the realities of the market place and capabilities of previous computer generations (Smith et al. 1987; Goodchild 1987). Because of conflicts in data storage structure (image rasters versus map vectors) there are only limited examples of geographic information systems that can fully interact with remotely sensed observations (e.g., the Image Based Information System (IBIS) at Jet Propulsion Laboratory) (Bryant and Zobrist 1976; Simonett 1988). In general, either the remotely sensed data have to be classified into nominal categories before entry into the GIS (so it can be "vectorized") or the vector geographic information must be "rasterized" before it is overlain, as another "image", in the image processing system. In either direction there is a loss of information (either precision of measurement or precision of location) (Tobler 1988). Such an approach is not able to accommodate biophysical interpretations of remotely sensed data.

Geographic Data and Cartography

The realization of global, integrative studies of the Earth's environment assumes that all the disjunctive data sources can be brought to some common framework which will permit interactive analysis. A computer-based geographic information system is, at its simplest, a computer data base management system that uses latitude and longitude, or a related spherical referencing scheme as its reference frame. Unfortunately no current GIS system uses this or a related reference frame. Most computer GIS systems today either implicitly assume a given map projection (e.g. State Plane Coordinates, Universal Transverse Mercator, etc.) or simple assume that the earth may be represented by a set of rectangular grids (the so-called Plate Carre representation).

GIS and Map Projections

Map projections provide a range of partial solutions to a basically unsolvable problem; the conversion of information located on a three dimensional sphere (the Earth) to a two-dimensional surface (maps). Each projection introduces certain distortions in either relative areal extent or direction which bias the relative significance of phenomena across the Earth. This conversion introduces problems in analytical geometry which, if not properly understood and handled, can create serious errors in interpretation (Tobler 1988; Willmont et al. 1985; Legates and J. 1986; Peuquet 1988).

GIS should have the capacity to ingest data from a range of map sources and place the observations in a common reference frame. This implies that the GIS should be capable of explicitly resolving the map projection of the source data and "inverse" map the observations; that is, recover of precise geographic location from projection information. This is apparently not in all cases yet possible mathematically (Marble and Peuquet 1985) and is rarely an element in existing GIS software.

Quality of the Input Data

Location

Before any serious efforts are undertaken to ingest a wide range of global geographical information into a common computer data base the question of true commonality must be resolved. Geographic referencing seems like a simple enough task. Location of observations on the earth's surface should be a fundamental requirement in measurement technologies However, precisely locating observations on the Earth is a difficult task. Large expenditures on satellite geopositioning systems clearly indicates the difficulties encountered in determining location. This suggests that perhaps the geographic integrity of terrestrial information is less precise than desirable.

Scale

For the types of point observations typically acquired by ground observers, problems occur when map production is faced. Interpolation and/or extrapolation between locations implies that the manner in which the particular observed phenomena changes in space (and time) between the observation points is understood. Any effort to map point information without this knowledge introduces unknown errors which may increase rapidly away from the point of observation. Efforts to employ these observations at finer scales than the original measurements introduce serious estimation errors.

Point versus Area Measurements

Remotely sensed observations have introduced a new set of location/scale problems because the sensors instantaneously and integratively observe large surface areas (Woodcock and Strahler 1987). How these remotely sensed area observations relate to the traditional point observations of the field scientist is uncertain for the same reasons that it is difficult to extrapolate and interpolate point measurements. Integration of the area measurements with typical ground point measurements is a fundamental problem in contemporary remote sensing and GIS research.

Toward Solutions

The current generation of mainframe supercomputers, minicomputers, workstations and potentially even microcomputers, now have such a large capacity to store and handle data This capacity should permit resolution of many of the current limitations. There is much evidence that suggests that there are real analytical advantages to hybrid GIS in which a range of data structures, including vector and raster, are permitted and encouraged (Smith et al. 1987; Peuquet 1983). Once such systems are widely available the current distinctions between numerical image processing and GIS are likely to disappear. The union of automated cartography within GIS and image analysis systems has not yet occurred, at least outside specialized research laboratories. However the heavy demands of cartographic mathematics appear to be particularly well addressed RISC integrated chips. As more computers incorporate this technology, the capacity to execute cartographic procedures in GIS operations is likely to become more common place. The innovation of satellite geopositioning systems will significantly improve the locational precision of future geographic data collections. The great remain problems are; 1) how to incorporate the relatively less precise historical observations currently available and 2) how to bridge between the typical point measurements of field researchers and the area measurements from remote sensing. These issues call upon the intellectual talents of earth scientists and others to resolve.

Conclusions

The current capacity of computer geographic information systems to address the complexities of divergent data sets from remote sensing systems and other sources is not sufficient to meet the substantial demands of global-scale environmental research. The impending expectations of the of the NASA Earth Observing System and the International Council of Scientific Unions Global Change program will quickly encounter these limitations. However, practitioners at more local scales (such as state and local planners and resource managers) are also constrained by these short comings. The precision and accuracy with which GIS and remote sensing can serve the purpose of provide adequate local and regional information is no less hindered by the limitations that the research scientist exploring the workings of the entire planet.

Major progress in the development of systems that can handle hybrid data formats, explicit cartography and data sets of varying quality and precision is sorely needed. Technological advances in computers appears to provide the capacity to handle these problems. However, the intellectual talents of scientists and engineers involved in these activities will be seriously challenged by these issues. The solutions to these problems, however, will not emanate strictly from isolated laboratory and research university. The day-to-day experiences of the local planner and manager in their attempts to employ this technology are likely to reveal current limitations and possible solutions not found in the abstract considerations of more theoretical environments. Every user of GIS and remote sensing technology should seriously consider themselves as participants in the development of this 21st century planetary perspective.

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SOURCES OF DATA FOR GEOGRAPHIC INFORMATION SYSTEMS

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INTRODUCTION

The three primary sources of data available to most geographic information system (GIS) users are government agencies, the private sector, and the users themselves. Government agencies offer a variety of digital and nondigital sources of data and information that can be useful to GIS operators. These products cover a broad spectrum of formats and information content, ranging from detailed thematic maps in graphic form to Compact Disc Read Only Memory with both data and display software. Each agency has a specific mission and mandate, and they produce maps and information to fulfill their goals. The data and information products may or may not suit the needs of a particular GIS. Private sector companies fill several roles in providing data for GIS including custom digitizing and selling repackaged and value-added data. Most GIS applications make use of data from both of these sources, but the best sources of current, relevant, large-scale data for a particular application may be the users themselves.

GIS AND DATA

The five components of a GIS are the data, hardware, software, people, and procedures that are used to collect, store, edit, analyze, manipulate, and output spatially distributed information. Of these five components, data represent the largest cost for a GIS, typically ranging from 50 to 80 percent of the life cycle expenditure. Because of this high cost, the questions of where to get data, how to use different formats, and how to store and manage data are extremely important to successful implementation of a GIS. Acquisition time for data adds significantly to the cost. Experienced GIS users know that the data acquisition and conversion portion of a 1-year GIS project is usually 11 months. All of the analysis is performed in the last month before the deadline. Data preparation includes a series of tasks ranging from drafting maps and digitizing to reformatting and quality checking digital sources, and most of these operations are labor intensive and time consuming.

GROWTH OF DATA REQUIREMENTS

GIS projects often grow beyond their original design as the manager and users discover the power of the GIS. This growth in requirements can lead to additional data acquisition problems, as illustrated by the following hypothetical example.

A park manager who has seen a GIS demonstration decides to get a system to do two things: update his park map and manage a new firewood cutting program. After acquiring and installing the hardware and software, the manager decides that five categories of information will satisfy the requirements of the two operations: roads, streams, park boundary, park facilities, and wood cutting areas.

The first two categories are available from the U.S. Geological Survey (USGS), and the park manager is able to digitize the remaining three. Everything works well, and he produces a new park map and manages the firewood cutting operation. His implementation is a complete success. The visitors enjoy the new map, and his boss gives him a promotion based on his initiative and ability to apply this powerful new computer tool. Everyone is so impressed, in fact, that additional tasks are proposed for the system. The new tasks are: (1) analyze surrounding land use, (2) identify habitat diversity, (3) analyze traffic flow, and (4) manage campsite reservations.

These requirements demand a much larger data base than the original system. The software will handle the analysis functions, and the only hardware change is a larger disk. Most of the work involved in handling the new requirements is focused on the data that must be collected. The expanded data categories of information include land use, land ownership, vegetation type, traffic data, and campsite characteristics.

All of these categories are very detailed and require information that is hard to obtain and needs frequent updating. When the users realize the capabilities of a GIS, they want to do more specific, sophisticated analyses, and usually only more extensive data collection will satisfy these requirements.

In summary, a GIS data base has the following characteristics:

- it is the most costly element,
- the data base always takes longer to build than planned, and
- users always want additional data.

GETTING DATA FROM GOVERNMENT AGENCIES DOESN'T ALWAYS WORK

Most GIS applications are sufficiently unique in information requirements or geographic area that government data sources are inadequate. USGS digital data illustrate several problems users encounter with government sources. (1) The original agency requirements may be different from another user's requirements. The USGS National Digital Cartographic Data Base (NDCDB) contains the digital versions of selected 1:24,000-scale primary map coverage for the United States. The digital data layers were designed to produce graphic products, and although they are topologically structured, this structure is not intended for use in a GIS. (2) The data format may not be appropriate to the user's needs. Digital data in the NDCDB are prepared, stored, and distributed in quadrangle format, yet most users need data coverages in other geographic boundaries, such as drainage basins or political subdivisions. (3) The resolution of the data may not match the user's GIS needs. The largest scale of USGS digital data is 1:24,000, which works well for some applications, but many users want digital data from larger scale maps. (4) Finally, the data may not be available. The NDCDB will not be completed until the year 2000, so certain areas have only partial coverage or none at all.

A major USGS GIS cooperative project illustrates the importance of the user's data in building a GIS. The USGS participated in a long term cooperative project with the Connecticut Natural Resources Center to assemble all available data for two 7.5-minute quadrangles and to demonstrate the capabilities of a GIS. The project team collected or digitized a total of 28 different categories of information. More than half of the data sets or maps were provided by the Natural Resources Center. The remainder, less than half, consisted of USGS or other government graphic or digital data.

In summary, digital categories of information from government agencies are useful in building a GIS, but their use may be limited because of their information content, format, scale, or areal coverage.

TYPES OF DATA

There are many types of data available for use in a GIS. The following descriptions highlight the characteristics of several of the most often used sources. Many government agencies produce both graphic and digital geographic information products. Each agency has its own methods for advertising and distributing these products, and for the present, the GIS user must find and contact each agency to get detailed information on coverage and content.

USGS GeoData

The mission of the USGS is to provide topographic, geologic, and hydrologic information that contributes to the wise management of our nation's natural resources. To fulfill this mission, the USGS produces map information in both graphic and digital form. In 1990, the USGS completed graphic coverage of the entire United States with primary quadrangle maps at 1:24,000 scale (1:63,360 in Alaska). Since 1980, the USGS has been building a digital map production capability and a digital data base. By the year 2000, the NDCDB should contain the data representing the primary map series as well as smaller scale maps. The elements of the NDCDB include Digital Line Graphs (DLG), Digital Elevation Models (DEM), the Geographic Names Information System (GNIS), and Land Use/Land Cover maps. The GNIS is a computer file with more than 2 million U.S. place names with latitude and longitude locations. Named features include towns, schools, and waterbodies, and a separate file contains all the topographic map names.

TIGER Data

Building on the cartographic base data prepared by the USGS, the Bureau of the Census, as part of the 1990 Census, produced the Topologically Integrated Geographic Encoding and Referencing (TIGER) System. TIGER, used to create the official 1990 Census map, is a computer data base with street maps; census map features including roads, railroads, and rivers; feature names and classification codes; and, within metropolitan areas, address ranges and ZIP Codes for streets. The TIGER data are available on magnetic tape and Compact Disc Read Only Memory, and the size of the entire U.S. file is 19,700 megabytes. This data set has great potential for GIS use, in spite of the following drawbacks: the TIGER file is not complete, many locations lack the precision required for large-scale GIS applications, and the currency of the data is not being maintained. Even with these flaws, the TIGER files represent a rich source of information that should be a part of the coverages in any GIS that requires transportation information, political boundaries, or address information.

Remote Sensing Data

A variety of remote sensing sources can be used in a GIS either in digital form or by digitizing from hard copy images. Scanned data from satellites are in row and column picture element (pixel) format, but usually require preprocessing for use in a GIS. The resolution, or area covered by a single pixel, depends on the altitude of the sensor and the characteristics of the sensing system. Pixel sizes for government and commercial satellites range from more than 1 km to 10 m. The four most common sources of remotely sensed data used in a GIS come from National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR), Earth Orbiting Satellite, Systemé Pour l'Observation de la Terre (SPOT), and from aerial photographs.

The NOAA operates a meteorological satellite that makes approximately 14 orbits per day. One of the sensors, the AVHRR with a 1.1-km pixel size at nadir collects data in five bands of the electromagnetic spectrum, two of which can be used in land resource investigations. An example of a derivative product from the AVHRR data is NOAA's global vegetation index data set, which is produced every week. This 20-megabyte data set consists of a 20-km resampled pixel size with a county boundary overlay. This data set is used by global change researchers to detect changes in regional vegetation patterns and as input to process models. Although the large pixel size limits the use of AVHRR data, the repetitive temporal coverage can be valuable in monitoring regional vegetation conditions and crop development.

The LANDSAT Thematic Mapper (TM) system produces images for seven bands of the electromagnetic spectrum. Six of these bands, covering the visible, near, and middle infrared portions of the spectrum, have a nominal pixel size of 30 m. LANDSAT TM images are used as background for the display of other map coverages, for classification of land cover, and in terrain rendering to show surface features in a perspective view.

One sensor onboard the SPOT satellite has a pixel resolution of 10 m. SPOT data have been used for natural resources management, land use classification, and map revision. In a number of applications, SPOT's resolution has been sufficient to replace more expensive aerial photography. In addition, the sensor can be aimed off nadir for stereo coverage that can be used to produce DEM's.

Experimental digital orthophotoquads have been produced by scanning 1:40,000-scale aerial photographs at a 52-micron resolution that yields an equivalent 2-m ground resolution. These orthophotoquads are valuable because of their high resolution and high degree of metric accuracy.

DATA SOURCES AND THE GIS USER

The specific mandates of Federal agencies may limit the wide application of the information they produce. Each information source has its strengths and weaknesses.

Overlaying USGS DLG Data and TIGER data on a SPOT image illustrates the choices that typically face a user. All three sources have transportation information in different forms and with different characteristics. The SPOT image has the most recent information, but it is not structured for use in a GIS and must be digitized. The DLG data are structured for GIS use and register well on the SPOT image, but because of the length of the revision cycle, have not kept pace with the area's rapid growth. The TIGER files are topologically structured and are more current than the DLG data because they are based on additional information sources, but have less precision and may not match the actual ground locations.

SHARING DATA IS THE ANSWER

Data management is the most significant GIS challenge of the nineties. The use of GIS's is increasing, but data collection is expensive and digital data sets are difficult to find. Also there is considerable duplication of effort in data collection. Improvement is needed in many areas.

The USGS vision for the future is a national spatial data infrastructure that includes a national GeoData system, enhanced data sharing, and a network of Federal, State, and commercial dealers who will offer standard services in state-of-the-art information products. With such an infrastructure in place, a GIS manager could query a single online computer index, review data sets that are available, and order the data needed.

The Federal Geographic Data Committee (FGDC), composed of Federal agencies involved in digital mapping activities, has been given responsibility for coordinating Federal Government mapping activities by the Office of Management and Budget. Under the guidance and sponsorship of the FGDC, a national data infrastructure can be built with participation and representation at all levels of government, as well as interaction with the private sector and universities. Only through this wide-ranging cooperative approach will data suppliers and GIS users be able to address the difficult data management challenges of the next decade.

CHAPTER FIVE[1]

ISSUES OF QUALITY AND UNCERTAINTY

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INTRODUCTION

Digital processing of cartographic data brings immense benefits in the form of rapid, precise and sophisticated analysis, but at the same time it reveals weaknesses which may not otherwise be apparent. Computers are very precise machines, and errors and uncertainties in data can lead to serious problems, not only in the form of inaccurate results but in the consequences of decisions made on the basis of poor data, and increasingly in legal actions brought by affected parties.

In this chapter we first review the dimensions of the accuracy problem, and discuss the premises and assumptions on which the remainder of the chapter is based. The second section reviews the models which are available for analyzing and understanding errors in spatial data. The chapter concludes with a summary of the current state of the art and an agenda for future research and development.

The terms accuracy, precision, resolution and scale are used almost interchangeably in reference to spatial data, but we will need to establish more exact definitions for the purposes of this discussion. **Accuracy** refers to the relationship between a measurement and the reality which it purports to represent. **Precision** refers to the degree of detail in the reporting of a measurement or in the manipulation of a measurement in arithmetic calculations. Finally, the **resolution** of a data set defines the smallest object or feature which is included or discernable in the data. Scale and resolution are intimately related because there is a lower limit to the size of an object which can be usefully shown on a paper map. This limit is often assumed to be 0.5mm as a rule of thumb, so the effective resolution of a 1:1,000 map is about 1,000 times 0.5mm, or 50cm,

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[1] Draft of a chapter to appear in *Cartographic Research Agenda in the 1990s*, edited by J.-C. Muller, to be published by Elsevier in 1991

0.5mm as a rule of thumb, so the effective resolution of a 1:1,000 map is about 1,000 times 0.5mm, or 50cm, although the standards of most mapping agencies are substantially better. The effective resolutions of some common map scales, assuming 0.5mm resolution, are shown in Table 5.1.

Table 5.1 about here

Because digital spatial data sets are not maps, and have no similar physical existence, they do not have an obvious scale, and it is common to think of such data as essentially scale-free. But this is to oversimplify. If the data were obtained by digitizing, their resolution is that of the digitized map. If they were obtained from imagery, their resolution is that of the pixel size of the imagery. In spite of appearances to the contrary, then, no spatial data is ever resolution free. The term 'scale' is often used loosely as a surrogate for database resolution.

DIMENSIONS OF THE PROBLEM

Precision

One of the widely accepted design principles of spatial data handling systems is that they should be able to process data without significant distortion. It is important when calculations are carried out on coordinates, for example, that the results should not be affected by lack of precision in the machine. We have seen that a figure of 0.5mm can be assumed to be typical for the resolution of an input map document. 0.5mm is also roughly the accuracy with which an average digitizer operator can position the crosshairs of a cursor over a point or line feature. Most digitizing tables have a precision of 0.25mm or better, thus ensuring that the table itself does not introduce additional distortion as points are captured.

If we take the size of the source map sheet on the digitizing table to be 100cm by 100cm, then a precision of 0.5mm represents an uncertainty of 0.05% relative to the size of the sheet, or an uncertainty in the fourth significant digit. So in order not to introduce distortion, internal storage and processing of coordinates must be correct to at least four digits. However seven or eight decimal digits are commonplace in arithmetic calculations in spatial data handling systems, and many GISs operate at much higher precision, in effect allowing GIS users to ignore the possibility of arithmetic distortion and to assume that internal processing is carried out with infinitely high precision.

Despite this, arithmetic precision, or lack of it, is sometimes a problem in spatial data processing. One common situation occurs when point locations are specified in a global coordinate system. For example, the UTM system assigns coordinates with respect to an origin on the equator, so locations in the mid-Northern latitudes will have one of their coordinates in the millions of metres. Processing of data taken from large scale maps, perhaps 1:1,000, will therefore require precision in the sixth or seventh significant digit. This can be particularly problematic in performing operations such as calculation of the intersection point of two lines, or the centroid of a parcel of land, where differences in the products of six or seven digit numbers become important.

Another artifact of high precision is well known in connection with polygon overlay operations. It is common to find that two coverages of different themes for the same area share certain lines. For example the shoreline' of a lake will appear both on a map of soils and a map of vegetation cover. When soils and vegetation cover are overlaid the two versions of the shoreline should match perfectly. In practice this is never the case. Even if the two lines matched perfectly on the input documents, errors in registration and differences in the ways in which the digitizer operators captured the lines will ensure different digital representations in the database. Moreover since the overlay operation is carried out to high precision, the differences are treated as real and become small sliver polygons. Table 5.2, from Goodchild (1979), shows the results of overlaying five layers from the Canada Geographic Information System, and the enormous numbers of very small polygons produced.

Table 5.2 about here

Several approaches have been taken to deal with the spurious polygon problem in polygon overlay, which has the annoying property that greater accuracy in digitizing merely leads to greater numbers of slivers. Some systems attempt to distinguish between spurious and real polygons after overlay, using simple rules, and to delete those which are determined to be spurious (see Figure 5.1). A suitable set of rules to define spurious polygons might be:

- small in area;
- long and thin in shape (high ratio of perimeter to square root of area);
- composed of two arcs only;

- both nodes have exactly four incident arcs.

In addition, the attributes of spurious polygons are characteristic. Suppose our soil map line marks the boundary between soils A and B, and our vegetation map shows the boundary between classes 1 and 2. Ideally, when overlaid the result should be a line with soil A and vegetation 1 on one side, and soil B and vegetation 2 on the other. Sliver polygons will be either soil B and vegetation 1, or soil A and vegetation 2. Moreover the attributes will alternate from one sliver to the next, as the soil and vegetation boundaries cross and recross (see Figure 5.1). So the detection of one spurious polygon provides additional evidence that nearby polygons are also spurious.

Figure 5.1 about here

Another approach to dealing with the sliver problem is in effect to reduce the precision of the overlay operation, by requiring the user to establish a tolerance distance. Any lines lying within the tolerance distance of eachother are assumed to be the same. A similar approach is often taken in digitizing, where two lines are assumed to join or 'snap' if the distance between them is less than some user-established tolerance distance (see Figure 5.2a).

Figure 5.2 about here

Because a tolerance distance is in effect a reduced level of spatial resolution, all objects or features smaller than the tolerance become ambiguous or indistinguishable. Figure 5.2c shows an example of a complex polygon with a narrow strait or isthmus. If the width of the strait is less than the tolerance distance, it is impossible to determine from the geometry of the feature alone whether it is indeed a single polygon with a narrow strait, or two polygons. In some cases it may be possible to resolve the ambiguity if the user has already identified labels or attributes for the polygon(s); if two labels have been input, it should be clear that the feature consists of two polygons. In such instances the **topology** (the existence of two polygons) is allowed to resolve ambiguity in the **geometry**.

The potential conflict between topology and geometry is a consistent theme in spatial data handling. Franklin (1984; Franklin and Wu 1987) has written about specific instances of conflict, and about ways of resolving them. For example, a point may be given an attribute indicating that it lies inside a given polygon, which might be a county, but geometrically, because of digitizing error or other problems, the point may lie outside the polygon (Blakemore 1984). The conflict may be resolved by moving the point inside the polygon, or by moving the polygon boundary to include the point, or by changing the point's attributes. The first two are examples of allowing topology to correct geometry, and the third of allowing geometry to correct topology. In all cases, and particularly in the second, the implications of a change on other objects and relationships must be considered; if the polygon's boundary is moved, do any other points now change properties? Unfortunately the propagation of changes of this type can have serious effects on the overall integrity of the database.

In summary, the average user will approach a GIS or spatial data handling system with the assumption that all internal operations are carried out with infinite precision. High precision leads to unwanted artifacts in the form of spurious polygons. Moreover in reducing effective precision in such operations as digitizing and polygon closure it is common for unwanted effects to arise in the form of conflicts between the topological and geometrical properties of spatial data. The ways in which system designers choose to resolve these conflicts are important to the effective and data-sensitive application of GIS technology.

Accuracy

Thus far we have used examples of the distortions and errors introduced into spatial data by digitizing and processing. However if we are to take a comprehensive view of spatial data accuracy it is important to remember that accuracy is defined by the relationship between the measurement and the reality which it purports to represent. In most cases reality is not the source document but the ground truth which the source document models. The map or image is itself a distorted and abstracted view of the real world, interposed as a source document between the real world and the digital database.

We will use two terms to distinguish between errors in the source document and in the digitizing and processing steps. **Source** errors are those which exist in the source document, and define its accuracy with respect to ground truth. **Processing** errors are those introduced between the source document and the GIS product, by digitizing and processing. We will find that in general processing errors are relatively easier to measure, and smaller than source errors.

All spatial data without exception are of limited accuracy, and yet it is uncommon to find statements of data quality attached to such data, whether in the form of source maps, images or digital databases. The accuracy of much locational or attribute data is limited by problems of measurement, as for example in the determination of latitude and longitude, or elevation above mean sea level. In other cases accuracy is limited by problems of definition, as when a soil type is defined using terms such as ‘generally’, ‘mostly’, ‘typically’ and thus lacks precise, objective criteria. Locations defined by positions on map projections are limited by the accuracy of the datum, and may change if the datum itself is changed.

More subtle inaccuracies result from the way in which a source document models or abstracts reality. For example an extended object such as a city may be shown at some scales as a point, or a census reporting zone may be located by its centroid or some other representative point (Bracken and Martin 1989). The

the source document and in the database by a simple line or sharp discontinuity. The attributes assigned to a polygon may not in fact apply homogeneously to all parts of the polygon, but may be more valid in the middle and less valid toward the edges (Mark and Csillag 1989). All of these errors result from representing spatial variation using objects; the objects are either of the wrong type for accurate representation, in the case of the city represented by a point, or used to model what is in fact continuous variation. Models such as these allow complex spatial variation to be expressed in the form of a comparatively small number of simple objects, but at a corresponding cost in loss of accuracy. Unfortunately the process of modeling has usually occurred in the definition of the source document, long before digitizing or processing in a GIS, and rarely is any useful information on levels of accuracy available.

Separability

Most digital spatial data models distinguish clearly between locational and attribute information. From an accuracy perspective, errors in location and attributes are often determined by quite different processes, and in these cases we term the two types of error **separable**. For example, a reporting zone such as a census tract may be formed from segments which follow street center lines, rivers, railroads and political boundaries. The processes leading to error in the digitizing of a river-based boundary are quite different to those typical of street center lines. Errors in imagery are similarly separable, attribute errors being determined by problems of spectral response and classification, while locational errors are determined by problems of instrument registration. The same is true to a lesser extent for topographic data, since errors in determining elevation at a point are probably only weakly dependent on errors in locating the point horizontally.

However in maps of vegetation cover, soils or geology, where polygon objects are commonly used to model continuous variation, the two types of error are not separable, as object boundaries are derived from the same information as the attributes they separate (Goodchild 1989). The transition zone between types A and B may be much less well defined than the transition between types A and C. The process by which such maps are created gives useful clues to the likely forms of error which they contain. A forest cover map, for example, will be derived from a combination of aerial imagery and ground truth. Polygons are first outlined on the imagery at obvious discontinuities. Ground surveys are then conducted to determine the attributes of each zone or polygon. The process may be iterative, in the sense that the ground survey may lead to relocation of the interpreted boundaries, or the merger or splitting of polygons. Figure 5.3 summarizes these processes of source error generation, and the subsequent steps which lead to processing errors.

Figure 5.3 about here

The forest example illustrates the relationship between different error processes particularly well. In forest management the homogeneous zones identified in the mapping process are termed **stands**, and become the basic unit of management. If a stand is cut and reseeded or allowed to regenerate, the processes determining its attributes may be no longer related to the processes determining its boundaries, and thus attribute and locational errors will become separable. Similarly, even in the initial map obtained from imagery and ground survey there will be boundary segments which follow roads, rivers or shorelines and again are subject to error processes which are independent of those affecting attributes.

The ideal

The arguments in the preceding sections lead to a clear idea of how an ideal GIS might be structured. First, each object in the database would carry information describing its accuracy. Depending on the type of data and source of error, accuracy information might attach to each primitive object, or to entire classes of objects. Accuracy might be coded explicitly in the form of additional attributes, or implicitly through the precision of numerical information.

Every operation or process within the GIS would track error, ascribing measures of accuracy to every new attribute or object created by the operation. Uncertainty in the position of a point, for example, would be used to determine the corresponding level of uncertainty in the distance calculated between two points, or in the boundary of a circle of specified radius drawn around the point.

Finally, accuracy would be a feature of every product generated by the GIS. Again it might be expressed either explicitly or implicitly in connection with every numerical or tabular result, and means would be devised to display uncertainty in the locations and attributes of objects shown in map or image form.

Of course the current state of GIS technology falls short of this ideal in all three areas. We currently lack comprehensive methods of describing error, modeling its effects as it propagates through GIS operations, and reporting it in connection with the results of GIS analysis. The remaining sections of this chapter describe the current state of knowledge and such techniques as currently exist for achieving a partial resolution of the error problem.

MODELS OF ERROR

Background

With the basic introduction to accuracy and error in the previous section, we can now consider the specific issue of quality in cartographic data. This is not a simple and straightforward extension; as we will see, spatial data requires a somewhat different and more elaborate approach.

The objective is to find an appropriate model of the errors which occur in cartographic data. A model is taken here to mean a statistical process whose outcome emulates the pattern of errors observed in real digital spatial data. The first subsection considers models of error in the positioning of simple points; the second section looks at the ways this can be extended to more complex line or area features.

Points

The closest analogy between the classical theory of measurement and the problem of error in cartographic data concerns the location of a single point. Suppose, for example, that we wished accurately to determine the location, in coordinates, of a single street intersection. It is possible to regard the coordinates as two separate problems in measurement, subject to errors from multiple sources. If the coordinates were in fact determined by the use of a transparent roamer on a topographic sheet, then this is a fairly accurate model of reality. Our conclusion might be that both coordinates had been determined to an accuracy of 100m, or 2mm on a 1:50,000 sheet. This is illustrated in Figure 5.4.

If the errors in both coordinates are represented by classic bell curves, then we can represent accuracy in the form of a set of ellipses centred on the point. If the accuracies are the same in each coordinate and if the errors are independent, then the ellipses become circles, again centred on the point. This gives us the circular normal model of positional error, as the two-dimensional extension of the classic error model. The error in position of a point is seen in terms of a bell-shaped surface centred over the point (Figure 5.4). The probability that any point is the true location is measured by the height of the surface of the bell over the point, and is clearly greatest at the measured location, decreasing symmetrically in all directions. Using the model we can compute the probability that the true location lies within any given distance of the measured location, and express the average distortion in the form of a standard deviation.

The **Circular Standard Error** is equal to the standard errors in the two coordinates, and can be portrayed by drawing a circle which passes through points representing one standard error to the left and right of the point in the x direction, and similarly above and below the point in the y direction (Figure 5.4). When the standard errors in x and y are not equal, the Circular Standard Error is approximated as the mean of the two. This approximation is valid only for small differences in the two standard errors, but it is difficult to imagine circumstances in which this would not be true. The probability that a point's true location lies somewhere within the circle of radius equal to the Circular Standard Error is 39.35%. The **Circular Map Accuracy Standard** (CMAS) requires that no more than 10% of the errors on a map will exceed a given value. For example, with a CMAS of 1mm, in order to meet the standard no more than 10% of points should be more than 1mm from their true positions. Under the circular normal model a radius of 2.146 times the circular standard error will contain 90% of the distribution, with 10% lying outside. The relationship between the CMAS and the circular standard error is therefore a ratio of 2.146.

These indices have been incorporated into many of the widely followed standards for map accuracy. For example, the NATO standards rate maps of scales from 1:25,000 to 1:5,000,000 as A, B, C or D as follows:

A: CMAS = 0.5mm (e.g. 12.5m at 1:25,000)
B: CMAS = 1.0mm (e.g. 25m at 1:25,000)
C: CMAS determined but greater than 1.0mm
D: CMAS not determined.

Many other mapping programs use CMAS as the basis for standards of horizontal or planimetric accuracy, and use similar values.

Lines and areas: the Perkal band

In vector databases lines are represented as sequences of digitized points connected by straight segments. One solution to the problem of line error would therefore be to model each point's accuracy, and to assume that the errors in the line derived entirely from errors in the points. This is illustrated in Figure 5.5. Unfortunately this would be inadequate for several reasons. First, in digitizing a line a digitizer operator tends to choose points to be captured fairly carefully, selecting those which capture the form of the line with the greatest economy. It would therefore be incorrect to regard the points as randomly sampled from the line, or to regard the errors present in each point's location as somehow typical of the errors which exist between the true line and the digitized representation of it.

Figure 5.5 about here

Secondly, the errors between the true and digitized line are not independent, but instead tend to be highly correlated (Keefer, Smith and Gregoire 1988; Amrhein and Griffith 1987). If the true line is to the east of the digitized line at some location along the line, then it is highly likely that its deviation immediately on either side of this location is also to the east by similar amounts. Much of the error in digitized lines results from misregistration, which creates a uniform shift in the location of every point on the map. The relationship between true and digitized lines cannot therefore be modelled as a series of independent errors in point positions.

One commonly discussed method of dealing with this problem is through the concept of an error band. Figure 5.6 shows the observed line surrounded by a band of width epsilon, known as the Perkal epsilon band (Perkal, 1956, 1966; Blakemore, 1984; Chrisman, 1982). The model has been used in both deterministic and probabilistic forms. In the deterministic form, it is proposed that the true line lies within the band with probability 1.0, and thus never deviates outside it. In the probabilistic form, on the other hand, the band is compared to a standard deviation, or some average deviation from the true line. One might assume that a randomly chosen point on the observed line had a probability of 68% of lying within the band, by analogy to the percentage of the normal curve found within one standard deviation of the mean.

Figure 5.6 about here

Some clarification is necessary in dealing with line errors. In principle, we are concerned with the differences between some observed line, represented as a sequence of points with intervening straight line segments, and a true line. The gross misfit between the two versions can be measured readily from the area contained between them, in other words the sum of the areas of the spurious or sliver polygons. To determine the mismatch for a single point is not as simple, however, since there is no obvious basis for selecting a point on the true line as representing the distorted version of some specific point on the observed line. Most researchers in this field have made a suitable but essentially arbitrary decision, for example that the corresponding point on the true line can be found by drawing a line from the observed point which is perpendicular to the observed line (Keefer, Smith and Gregoire, 1988). Using this rule, we can measure the linear displacement error of any selected point, or compute the average displacement along the line.

Although the Perkal band is a useful concept in describing errors in the representation of complex objects and in adapting GIS processes to uncertain data, it falls short as a stochastic process model of error. An acceptable model would allow the simulation of distorted versions of a line or polygon, which the Perkal band does not, and would provide the basis for a comprehensive analysis of error.

Alternatives to the Perkal band

Goodchild and Dubuc (1987) have described a stochastic process which might be used to simulate the effects of error in soil, vegetation or forest cover maps. Consider the surface shown in Figure 5.7, which has the following properties. It is continuous, the elevation at every grid cell being a small displacement up or down from its neighbors, and therefore strongly spatially autocorrelated. It is also random, the surface having been generated by one of a number of stochastic processes known to produce random fields of this nature. In fact the surface was generated by the fractional Brownian process (Mandelbrot, 1982), although other methods such as moving bands, spatially autoregressive and Markov processes have been described (for review see Haining, Griffith and Bennett, 1983). The fractional Brownian process has the property of self-affinity, that is, in principle, that any part of the surface if suitably expanded would be indistinguishable in its statistical properties from the surface as a whole.

Figure 5.7 about here

Suppose now that the surface is classified by assigning each pixel or grid cell a color or class based on its elevation, using a set of elevation classes or ranges. The result would be a standard contour map, in which the image is divided into a number of bands, each corresponding to a range of elevation, with the rule that classes may not be adjacent in the image unless the corresponding ranges of elevation are adjacent. The boundaries of the polygons so formed may not intersect. Finally, boundaries can be distorted to simulate the effects of digitizing errors by adding a suitably autocorrelated surface of small relief to the existing one and recontouring.

To simulate the appearance of a soil or vegetation map, Goodchild and Dubuc (1987) took two independently generated surfaces and passed each pixel through a simple classifier as in the example shown in Figure 5.8. This process is analogous to the control of ecological zones by temperature and precipitation in the model of Holdridge et al. (1971). The resulting map has the required properties; boundaries intersect in nodes, and have a degree of fragmentation and boundary wiggliness which depends on the ruggedness of the underlying surfaces. Distorted versions of the map can be produced by adding autocorrelated surfaces to one or both of the underlying surfaces, as in the two versions of the same map crossclassified in Table 5.3. Moreover the degree of distortion generated in each line will be a function of the classes which the line separates. In the simulated map shown in Figure 5.9 the boundaries have been smoothed by using a spline function, simulating the tendency of interpreters to smooth out lines of discontinuity in images.

Figure 5.8 about here

Figure 5.9 about here

The model is useful as a simulation of the distortion process which can be used to study the effects of uncertainty on GIS operations. However the number of parameters in the model, which include the number and properties of the underlying surfaces, the pixel size, the spline function and the classifier, argues against its calibration against real data and therefore against its use in characterizing the error in real datasets. In practice, GIS source maps tend to be highly abstracted, and to contain very little information on which a practical model of error might be based. It is only by returning to the original sources of the map's information that we can learn more about the nature of map error. In fact the map itself may be a barrier to better error modeling, by interposing a high level of abstraction between the raw data and the spatial database. Error modeling might be much easier if the raw imagery and ground surveys could be used to create a spatial database, and the abstract map obtained from the database by some objective process, rather than the reverse.

When the source of information is a remotely sensed image, a similar situation arises when pixels are classified and the result passed to a GIS for analysis, as this process similarly discards information which might be useful in modeling error. Many classification methods generate probabilities of class membership for each pixel, although usually only the most likely class is used. If the complete set of probabilities were passed to the GIS, then it would be possible to use these as the basis for uncertainty in GIS products. Goodchild and Wang (1988) describe a stochastic process of object distortion based on this concept. In effect, both of these methods provide links between uncertainty in the continuous variation of a field, and uncertainty in the objects used to model the field in a spatial database for phenomena such as soils and vegetation.

Models for dot and pixel counting

One of the traditional methods of measuring area from a map involves placing an array of grid cells or dots over the area to be measured, and counting. In principle this process is similar to that of obtaining the area of a patch from an image by counting the pixels which have been classified as belonging to or forming the patch. The accuracy of the area estimate clearly depends directly on the density of dots or the pixel size, but so does the cost of the operation, so it would be useful to know the precise relationship in order to make an informed judgment about the optimum density or size.

The literature on this topic has been reviewed by Goodchild (1980). In essence two extreme cases have been analyzed, although intermediates clearly exist. In the first the area consists of a small number of bounded patches, often a single patch; in the second, it is highly fragmented so that the average number of pixels or dots per fragment of area is on the order of one or two. We refer to these as cases A and B respectively. Case A was first analyzed by Frolov and Maling (1969), and later by Goodchild (1980). The limits within which the true area is expected to lie 95% of the time, expressed as a percentage of the area being estimated, are given by:

$$\pm\ 1.03\ (kn)^{1/2}\ (SD)^{-3/4} \tag{5.1}$$

where n is the number of patches forming the area;

k is a constant measuring the contortedness of the patch boundaries, as the ratio of the perimeter to 3.54 times the square root of area (k=1 for a circle);

S is the estimated area; and

D is the density of pixels per unit area.

The results for Case B follow directly from the standard deviation of the binomial distribution, since this case allows us to assume that each pixel is independently assigned. The limits within which the true area is expected to lie 95% of the time, again as a percentage of the area being estimated, are given by:

$$\pm\ 1.96\ [1 - \acute{S}/S_0]^{1/2}\ (S/D)^{1/2} \tag{5.2}$$

where S_0 is the total area containing the scattered patches.

Error rises with the 3/4 power of cell size in case A, but with the 1/2 power in case B. Thus a halving of cell size will produce a more rapid improvement in error in case A, other things being equal, because only cells which intersect the boundary of the patch generate error in case A, whereas all cells are potentially sources of error in case B, irrespective of cell size.

Error in images

Images such as those derived from remote sensing are composed of pixels (picture elements) of uniform size and shape, with associated measures of reflected or emitted radiation. After classification, each pixel is assigned to one of a number of classes, often of land use or land cover. Unlike the cartographic case, there are no objects or features to be located, and accuracy is simply a function of the errors in the assignment of classes to each pixel. The standard method of measuring accuracy in a classified image is to compare the classes assigned to a sample of pixels to the true classes on the ground ('ground truth') and express the result in the form of a table, the rows representing the assigned class and the columns the ground truth. Pixels which fall on the diagonal of the table are correctly classified; pixels which fall off the diagonal in a column are termed 'errors of omission' since the true value is omitted from the assigned class; and pixels which fall off the diagonal in a row are termed 'errors of comission' since they appear as false occurrences of a given class in the data. The contents of the table can be summarized in statistics such as the percentage of cells correctly classified, or using Cohen's Kappa statistic, which allows for correct classification by chance (see Congalton, Oderwald and Mead 1983; van Genderen and Lock 1977; van Genderen, Lock and Vass 1978; Greenland, Socher and Thompson 1985; Mead and Szajgin 1982; Rosenfield 1986; Rosenfield and Fitzpatrick-Lins 1986).

PROJECTIVE SUMMARY

As we have seen, techniques for dealing with uncertainty in spatial data are much better developed in some areas than others. Uncertainties in point locations are comparatively easy to deal with, and a significant proportion of geodetic science is devoted to dealing with the issue of accuracy in control networks. Substantial progress has been made in modeling the error introduced by digitizing, and in predicting its effects on the measures of perimeter and area of objects (Griffith 1989; Chrisman and Yandell 1988). But the more general problem of modeling the accuracy of spatial data with respect to ground truth remains. In part this is because of the complexity of the processes involved, and in part because many ground truth definitions are themselves uncertain. But in addition, we have seen how the representation of spatial variation as objects acts in many cases to make error modeling more difficult, simply because of the nature of the object data model. Both of the models of error in area-class maps presented above are defined first in terms of continuous variation, using the raster data model, and then used as the basis for deriving uncertainty in objects. If the accuracy issue leads us to question the use of traditional data models then any progress will certainly be slow.

The accuracy of spatial databases is the topic of the first research initiative of the National Center for Geographic Information and Analysis (NCGIA), which began with a meeting of specialists in Montecito, CA in December 1988. The collection of papers from that meeting has been published (Goodchild and Gopal 1989) and provides a broad overview of the accuracy issue in spatial data handling generally. The meeting identified an eleven-point research agenda:

- data structures and models;
- models of error and distortion;
- error propagation;
- product uncertainty and sensitivity;
- risk analysis;

- accuracy concerns among users and agencies;
- experimentation and measurement;
- error reduction methods;
- interpolation and surface modeling;
- aggregation, disaggregation and modifiable areal units;
- regularity and stability.

If accuracy is a problem in spatial data handling because of the high precision of the handling system, then one rational approach would be to reduce precision to match accuracy. In effect this is what happens in a raster system. Dutton (1984 1989; see also Goodchild and Yang 1989) makes this point, and proposes a tesseral scheme for global data that would replace common coordinate referencing with a finite-resolution hierarchical key.

There has been substantial progress in recent years in understanding the propagation of uncertainty that occurs in spatial data handling. Newcomer and Szagin (1984) and Veregin (1989c) have discussed error propagation during simple Boolean overlay; Lodwick (1989; Lodwick and Monson 1988) and Heuvelink et al. (1989) have analyzed the sensitivity of weighted overlay results to uncertainty in the input layers and weights; and Arbia and Haining (1990) have analyzed a general model of uncertainty in raster data. However overlay is perhaps the most simple of the primitive spatial data handling operations. Much more research is needed on the effects of buffering (dilating) uncertain objects, and of changing from one data model to another, e.g. raster/vector conversion.

If traditional map data models tend to give a misleading impression of the reliability of data, it is not surprising that many cartographic products fail to make the user aware of uncertainties. The move to standards of data quality (see Chapter 12) is a significant step toward greater awareness of the reliability of spatial data, and includes concepts of lineage, consistency and completeness as well as the more statistical issues discussed in this chapter. It is particularly important as GIS users continue to apply spatial data to purposes for which they may not have been designed.

This chapter has covered a range of material broadly connected with the issue of accuracy in spatial databases. As we noted at the outset, there are good reasons for believing that GIS technology will enhance our sensitivity to the nature of spatial data, and will increase the need to develop comprehensive and precise models of its errors and distortions. This enhanced understanding is likely to come not from study of the abstract objects which populate our maps and databases, but from the processes which created spatial variation in the first place and by which that variation was interpreted and modeled. In this sense GIS technology will help to fill many of the gaps which currently exist in our understanding of spatial differentiation and the processes which produce it.

It seems unlikely that the ideal accuracy-sensitive GIS which was outlined earlier in this chapter will ever become a reality. Its analog in simple, aspatial measurement, the statistical analysis system which tracks uncertainty as an attribute of each of its data elements and through each of its procedures, is also readily justified but equally far from implementation at this time. On the other hand standard errors of estimate and confidence intervals are a common product of statistical systems, and it is not difficult to imagine similar products from GIS procedures.

One of the results of the information age is an erosion of the role of the central data collection agencies, and society has not yet begun to come to grips with a growing need to reorganize the entire system of public data provision. It is now possible to determine position at low cost and at any location using satellite receivers, and to do so with an accuracy which exceeds that of the USGS 1:24,000 map series or other readily available and authoritative sources. Population counts from local agencies are increasingly being used as alternatives to those of the Bureau of the Census. Accuracy is now increasingly seen as an attribute of spatial information, and as a component of its value to decisionmakers. In some areas its associated costs can be dramatic, when disputes based on spatial information involve litigation. The complex relationships between accuracy and cost in the GIS area will be a challenging area for research for many years to come.

PRACTITIONER'S SUMMARY

The measurement of data quality in cartographic products is dealt with in numerous publications and standards, many of them referenced in this chapter. Perhaps the most comprehensive view of cartographic data standards is that developed in the US by the Digital Cartographic Data Standards Task Force (DCDSTF 1988), which provides a five-fold model for describing data quality, although it sets no precise numerical thresholds in any of the five categories and defines no standard measurement procedures.

This chapter has taken the view that measurement of data quality for the digital databases now being developed to support GIS is substantially different from measurement of the accuracy of cartographic features. In fact the two questions "Is this feature correct?" and "What is at this place?" require entirely different strategies. Some of these already exist, particularly in the feature-oriented domain, because they have been developed in support of traditional map-making. Others, particularly in the GIS-oriented domain, are still very limited and inadequate. Despite recent advances, the GISs of 1990 still regard the contents of the database as perfectly accurate, and make no attempt to estimate the uncertainties which are inevitably present in their products.

To summarize the state-of-the-art, we have good techniques for describing and measuring:

- the accuracy of location of a single point;
- the accuracy of a single measured attribute;
- the probability that a point at a randomly chosen location anywhere on a map has been misclassified;
- the effects of digitizing error on measures of length and area;
- the propagation of errors in raster-based area class maps through GIS operations such as overlay; and
- the uncertainty in measures of area derived from dot counting.

However many of these are still in the domain of research literature, and we are in a very early stage of implementing them in standard practice.

From a practical point of view, the coming decade will see a greater awareness of the problems caused by uncertainty in the manipulation and analysis of geographical data, driven largely by the increasing availability of GIS. There will be increasing awareness also of the distinction between accuracy of cartographic features, and accuracy of GIS databases and products. We will see the emergence of systems equipped with tools for tracking uncertainties and the lineage of data through complex series of operations, allowing the user to visualize and interact directly with such information through graphic interfaces. And finally, we will see increasing pressure on the providers of data to supply information on data quality.

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Table 5.1

Scale and resolution for some common map scales

Scale	Effective resolution
1:1,250	62.5cm
1:10,000	5m
1:24,000	12m
1:50,000	25m
1:100,000	50m
1:250,000	125m
1:500,000	250m
1:1,000,000	500m
1:10,000,000	5km

Table 5.2

Polygons by area for five CGIS layers and overlays

Acres	1	2	3	4	5	1+2+5	1+2+3+5	1+2+3+4+5
0-1	0	0	0	1	2	2640	27566	77346
1-5	0	165	182	131	31	2195	7521	7330
5-10	5	498	515	408	10	1421	2108	2201
10-25	1	784	775	688	38	1590	2106	2129
25-50	4	353	373	382	61	801	853	827
50-100	9	238	249	232	64	462	462	413
100-200	12	155	152	158	72	248	208	197
200-500	21	71	83	89	92	133	105	99
500-1000	9	32	31	33	56	39	34	34
1000-5000	19	25	27	21	50	27	24	22
>5000	8	6	7	6	11	2	1	1
Totals	88	2327	2394	2149	487	9558	39188	90599

Figure captions

5.1 Generation of sliver polygons in overlay

5.2 Tolerance problems in digitizing

a) undershoot; b) overshoot; c) narrow strait or isthmus

5.3 Stages in the creation of a forest cover layer

5.4 The circular normal model of errors in point locations

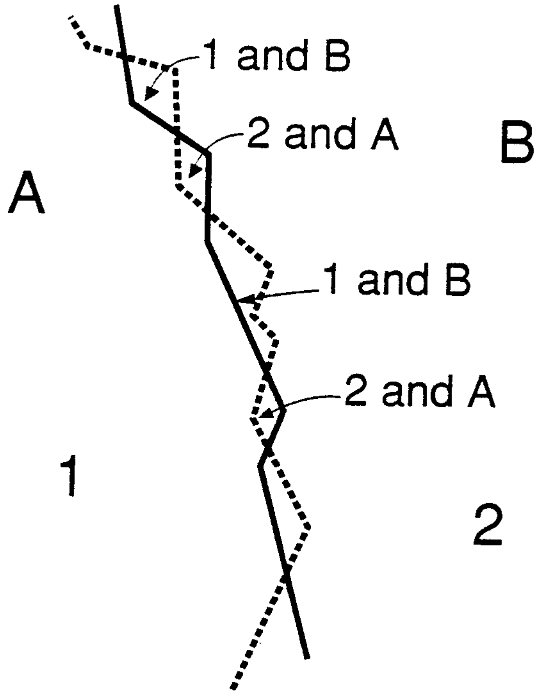
5.5 Model of line distortion based on independent uncertainties in each digitized point

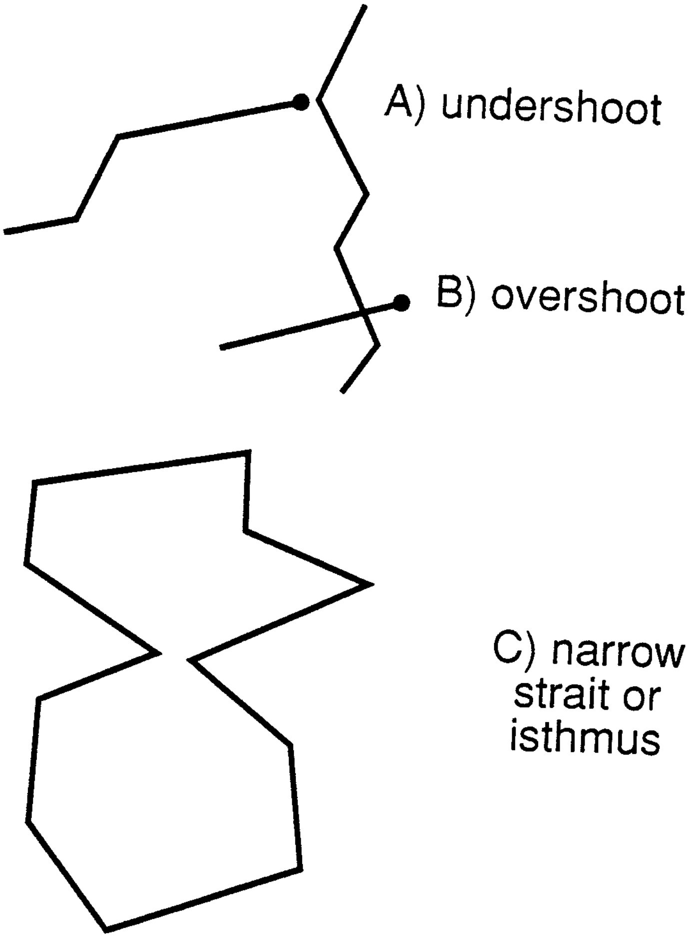
5.6 The Perkal epsilon band

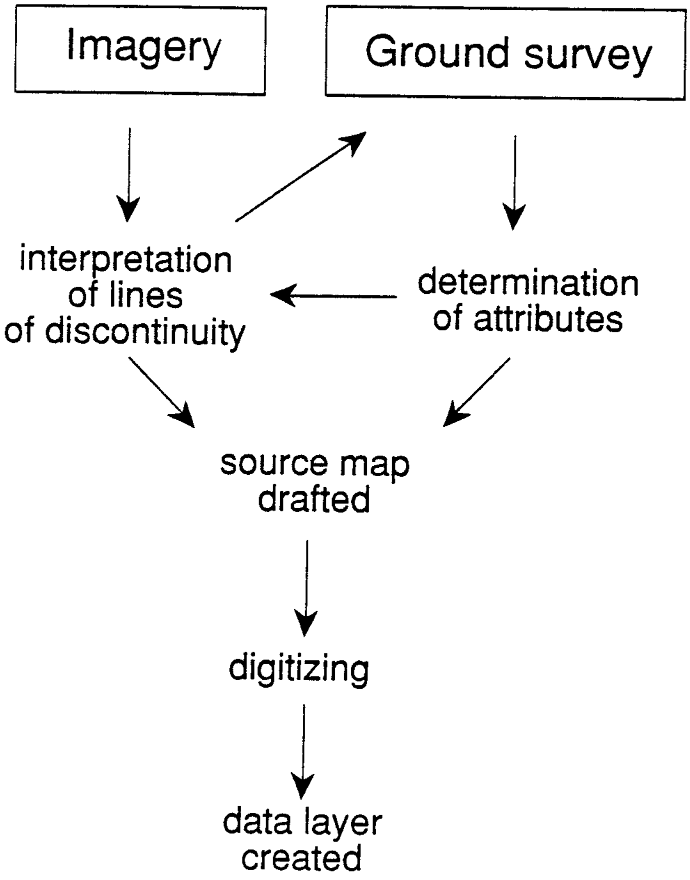
5.7 A spatially autocorrelated surface (random field) generated by the fractional Brownian process

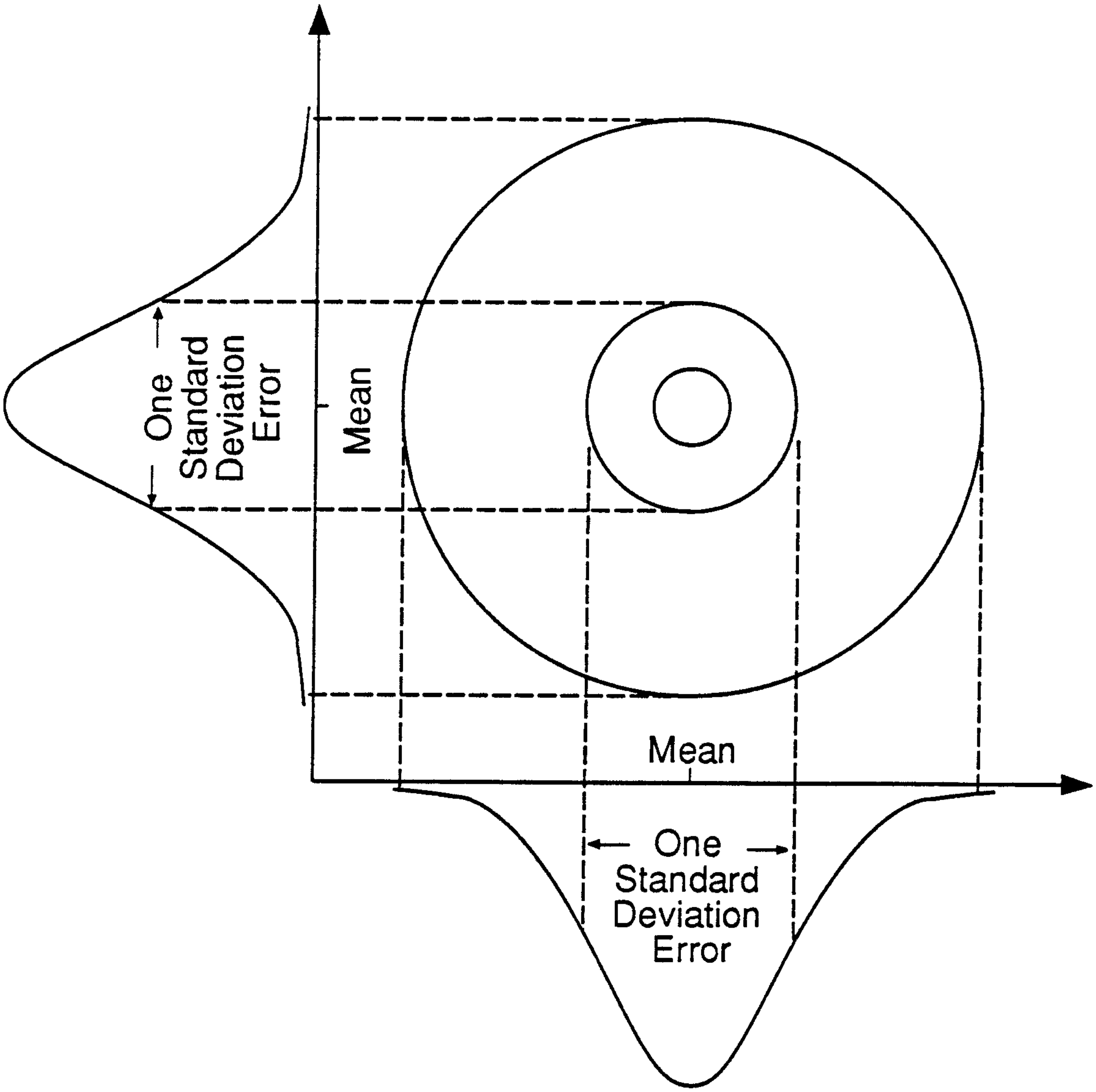
5.8 Use of a simple classifier to convert continuous surfaces to simulated area objects

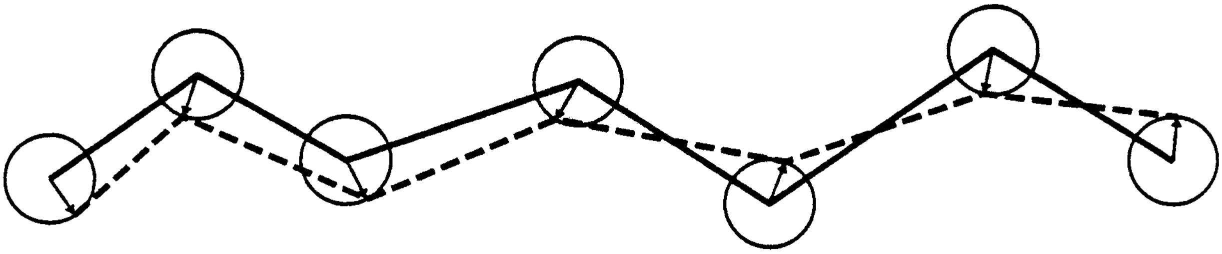
5.9 Simulation of area objects by the method of Goodchild and Dubuc (1987)

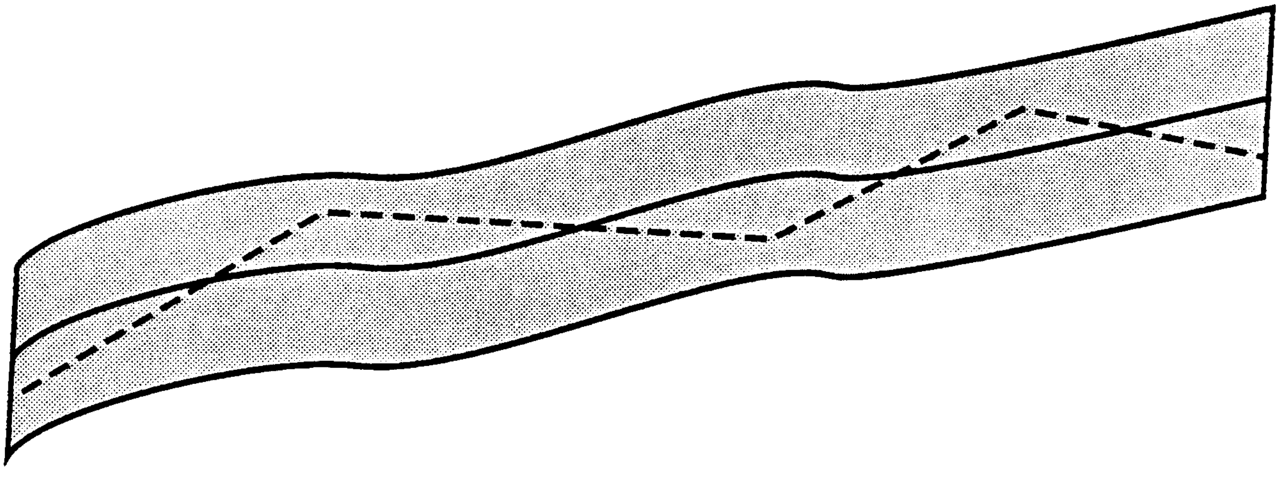

1 and B
2 and A
B
A
1 and B
2 and A
1
2

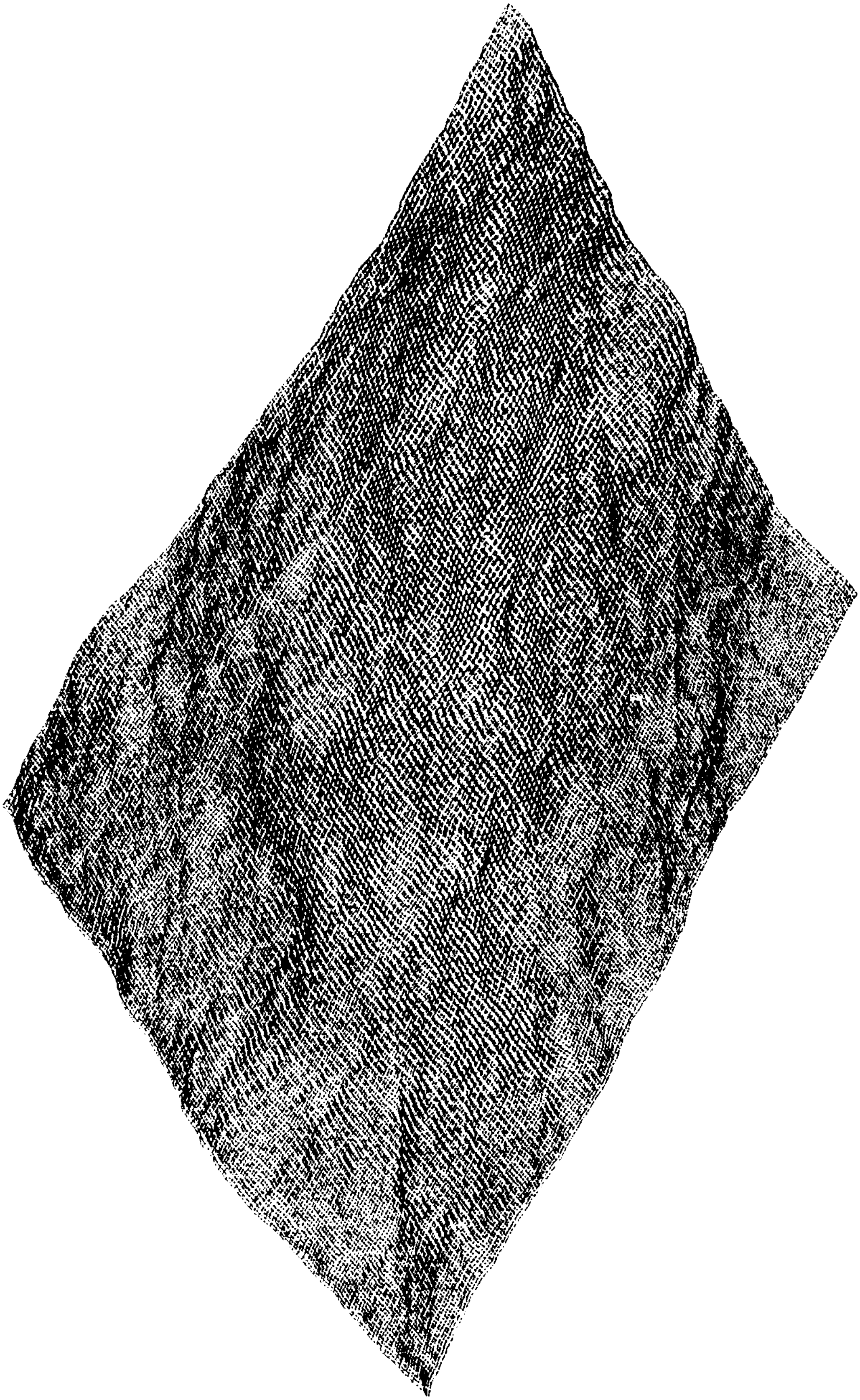

A) undershoot
B) overshoot
C) narrow strait or isthmus

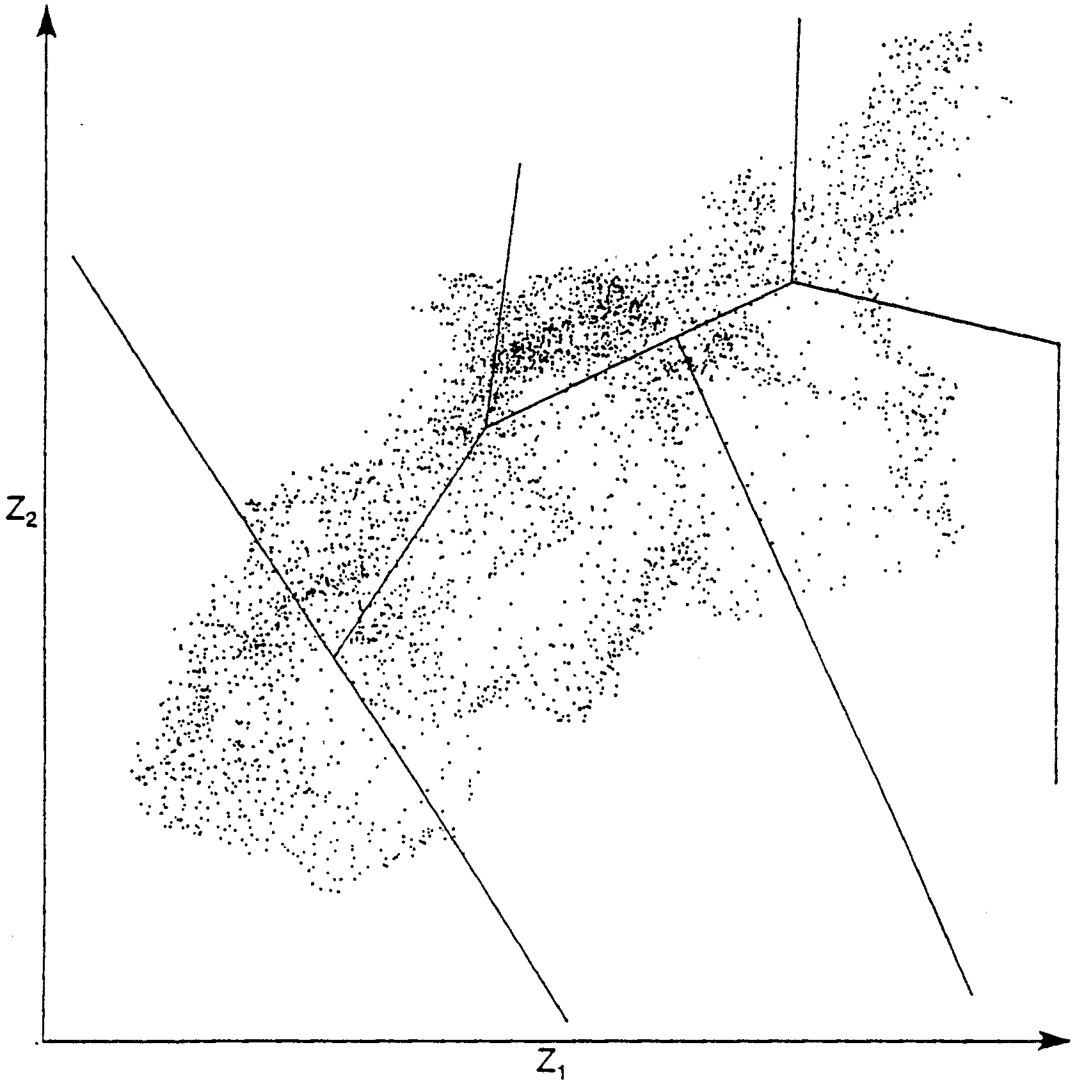

Imagery
Ground survey
interpretation of lines of discontinuity
determination of attributes
source map drafted
digitizing
data layer created

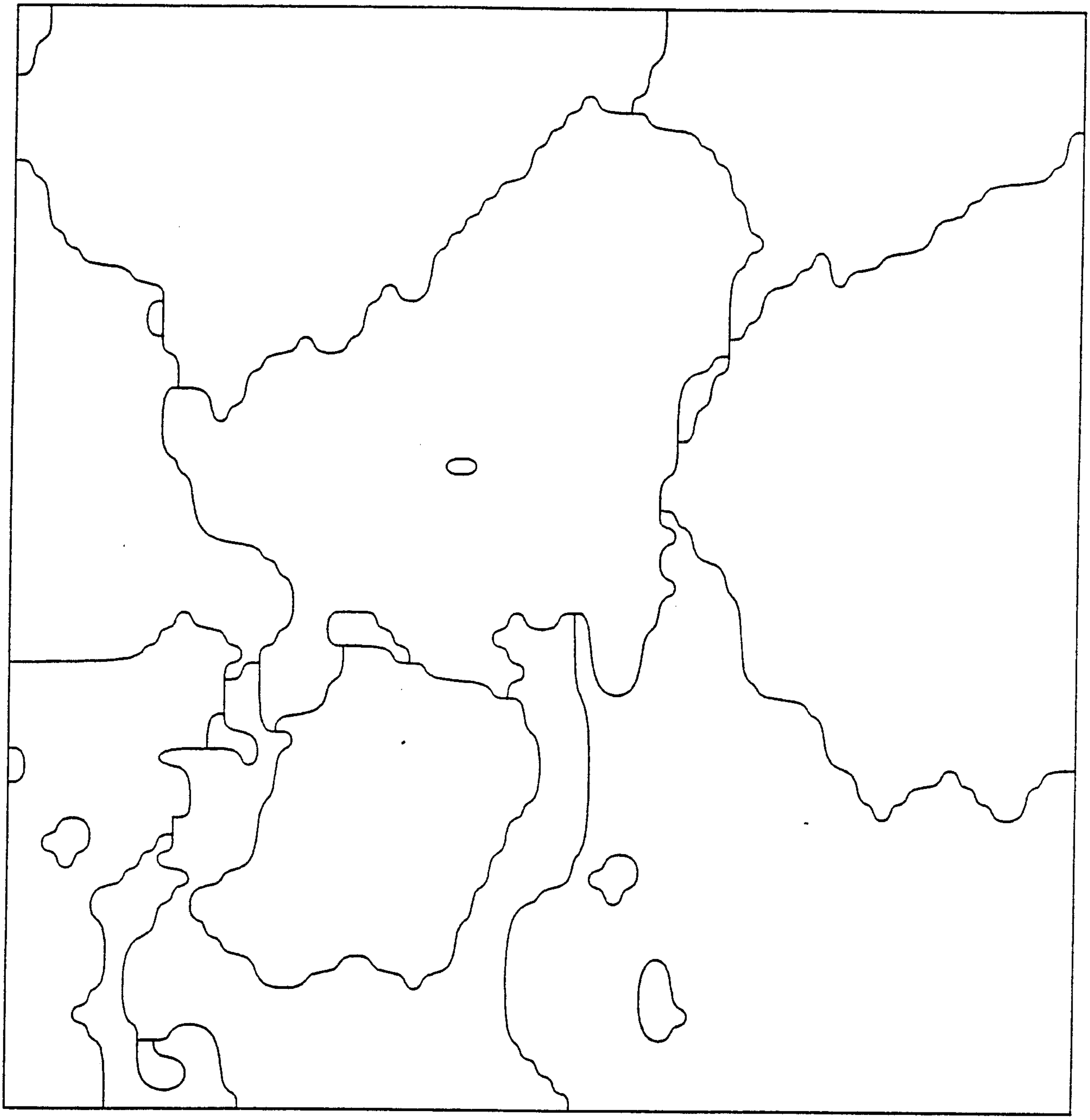

One Standard Deviation Error
Mean
Mean
One Standard Deviation Error








Z2
Z1



Combining Satellite, Meteorological, and Geographic Information for Monitoring Crop and Climatic Conditions in the Midwest United States

by

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ABSTRACT

Satellite derived climatic and crop related indices were computed from visible and near-infrared data acquired by the NOAA Advanced Very High Resolution Radiometer. The satellite derived indices were compared to traditional (ground observed) climatic and crop related variables for counties in the U.S. Corn Belt to determine if the satellite indices might be used to supplement the information available from the ground observed variables. The satellite derived indices did appear to supplement the information provided by ground observations and for one county included in the analysis, better represented the climatic and crop conditions of the entire county than the single location ground observed data. While useful for providing information to supplement ground observed data, the greatest use of the satellite observed data might be to verify the spatial application of ground observations, which are often used to represent relatively large areas.

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INTRODUCTION

Visible (0.58 to 0.68 µm) and near-IR (0.72 to 1.0 µm) data acquired by the National Oceanic and Atmospheric Administrations' Advanced Very High Resolution Radiometer (AVHRR) have been utilized by numerous researchers to compute vegetation indices. The indices utilize the characteristics of green vegetation that include absorption of radiation in the visible, and reflectance in the near-infrared, portions of the solar spectrum.

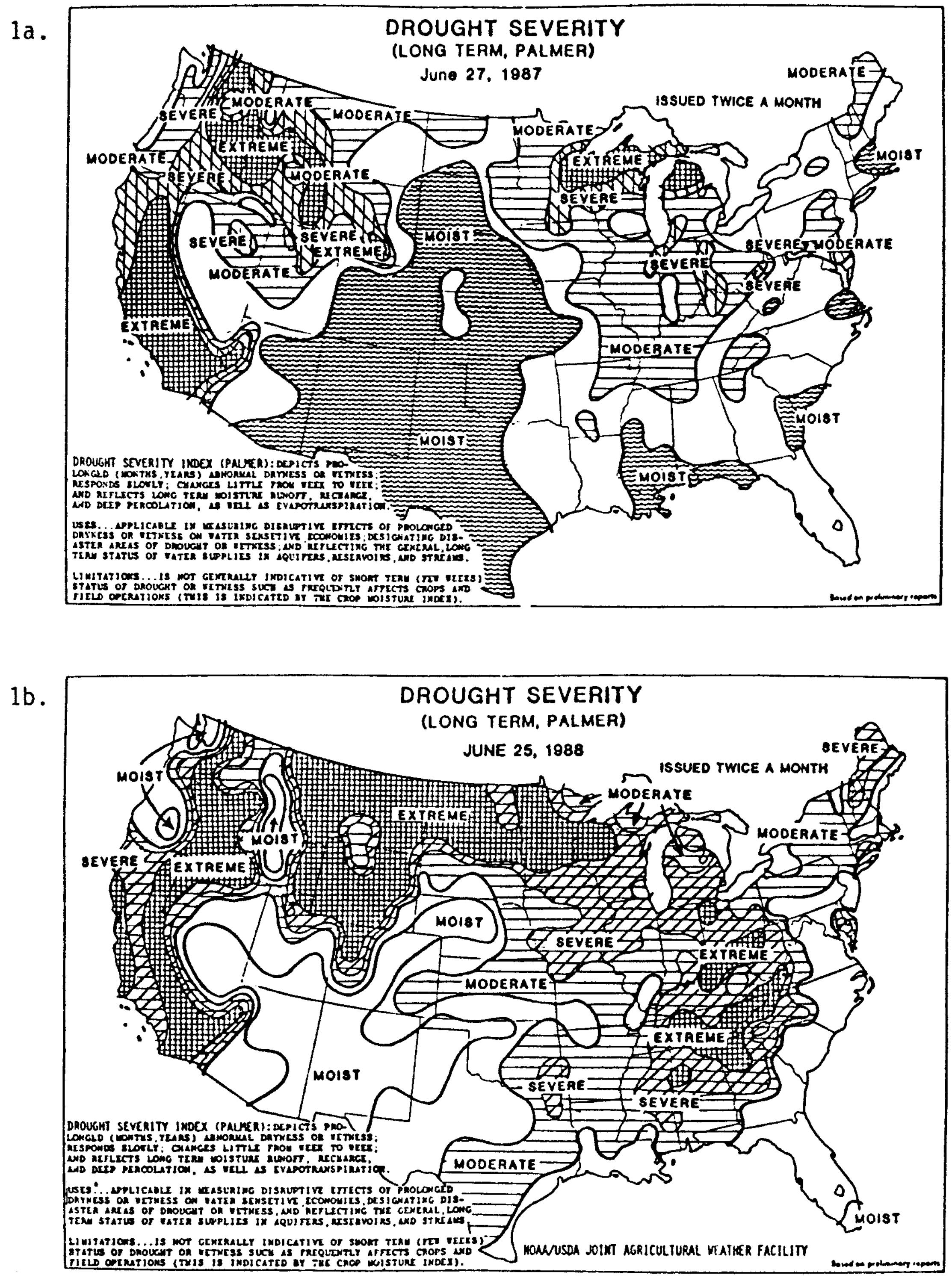
Vegetation indices observed in field experiments have been found to provide an indirect measure of the fraction of photosynthetically active radiation absorbed by the vegetation (Hipps et al., 1983; Gallo et al., 1985), an important factor in the production of plant phytomass. Satellite derived vegetation indices have been used to monitor vegetation development and the length of crop growing seasons (Gallo and Flesch, 1989; Malingreau, 1986). Daughtry et al. (1983) suggested how remotely sensed data, with ancillary information, might be used to monitor crop production.

Satellite derived data provide a synoptic, multidate views of large areas, and thus may supplement geographic, climatic, and crop data that are normally acquired at specific locations. The objectives of this study were to compare satellite derived vegetation index data with other methods of climatic and crop monitoring and develop methods for combining the unique information provided multiple sources of data.

MATERIALS AND METHODS

Study Location: U.S. Corn Belt

The 1987 and 1988 growing seasons were selected for evaluation of the satellite derived vegetation indices because of the differences in the seasonal climatic conditions that occurred in the U.S. Corn Belt these two years. Normal June through August precipitation within the Climatic Divisions (CD) of the Corn Belt states of Iowa, Illinois, and Indiana (NOAA, 1981) varies from 28 cm (11.0 inches) to 33.5 cm (13.2 inches). Precipitation within the region in 1987 (NOAA/USDA, 1987a) ranged from 75 to greater than 200% of the normal, while in 1988 (NOAA/USDA, 1988a) precipitation through most of the region was less than 75% of the normal values and portions of the region experienced less than 50% of the normal. During late June of 1987 much of the Corn Belt was determined to have a Drought Severity Index (Palmer, 1965) of "Moderate" (Figure 1a), the Index during 1988 at this time was "Severe" (Figure 1b). By late August the Index in the Corn Belt during 1987 (NOAA/USDA, 1987b) indicated that long-term moisture conditions had improved and were considered "Normal" to "Moist". During 1988, however, drought conditions persisted and through



1a.

DROUGHT SEVERITY INDEX (PALMER): DEPICTS PROLONGED (MONTHS, YEARS) ABNORMAL DRYNESS OR WETNESS; RESPONDS SLOWLY; CHANGES LITTLE FROM WEEK TO WEEK; AND REFLECTS LONG TERM MOISTURE RUNOFF, RECHARGE, AND DEEP PERCOLATION, AS WELL AS EVAPOTRANSPIRATION.

USES...APPLICABLE IN MEASURING DISRUPTIVE EFFECTS OF PROLONGED DRYNESS OR WETNESS ON WATER SENSITIVE ECONOMIES; DESIGNATING DISASTER AREAS OF DROUGHT OR WETNESS; AND REFLECTING THE GENERAL, LONG TERM STATUS OF WATER SUPPLIES IN AQUIFERS, RESERVOIRS, AND STREAMS.

LIMITATIONS...IS NOT GENERALLY INDICATIVE OF SHORT TERM (FEW WEEKS) STATUS OF DROUGHT OR WETNESS SUCH AS FREQUENTLY AFFECTS CROPS AND FIELD OPERATIONS (THIS IS INDICATED BY THE CROP MOISTURE INDEX).

1b.

DROUGHT SEVERITY INDEX (PALMER): DEPICTS PROLONGED (MONTHS, YEARS) ABNORMAL DRYNESS OR WETNESS; RESPONDS SLOWLY; CHANGES LITTLE FROM WEEK TO WEEK; AND REFLECTS LONG TERM MOISTURE RUNOFF, RECHARGE, AND DEEP PERCOLATION, AS WELL AS EVAPOTRANSPIRATION.

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Figure 1. Palmer Drought Severity Index for late June of 1987 (a) and 1988 (b) for the conterminous USA.

most of the Corn Belt the long-term conditions were considered "Severe" to "Extremely" dry (NOAA/USDA, 1988b).

County Analyses

Visible and near-IR data (1 km resolution at nadir) acquired by the NOAA-10 AVHRR and processed at the USGS/NMD EROS Data Center in Sioux Falls, SD were utilized in this study. The NOAA-10 satellite has a local overpass times of 0720 and 1920. Although the satellite observes the Earth at low solar elevation angles (approximately 20° on 1 April and 7 Sept. to 32° on 21 June) at the 0720 "morning" observation, the frequency of cloud-free observations was much greater than available from the "afternoon" satellite (NOAA-9 during 1987 and 1988). Cloud-free observations from NOAA-10 were available for the region at 7 to 10 day intervals through most of the 1987 and 1988 growing seasons.

The visible and near-IR satellite data associated with the scenes selected for the 1987 and 1988 growing seasons were calibrated (Rao, 1987) and geometrically registered to a Universal Transverse Mercator projection. The data were projected at a 1 km cell size with the AVHRR Data Acquisition and Processing System (ADAPS) software at the EROS Data Center. Several of the functions utilized in the data processing were modules included in the Land Analysis Software (LAS, 1990) developed at the USGS EROS Data Center and NASA's Goddard Space Flight Center.

The visible and near-IR data were utilized to compute Normalized Difference (ND) Vegetation Index:

$$ND = (\text{near-IR} - \text{visible}) / (\text{near-IR} + \text{visible}) \qquad [1]$$

values for each 1 km cell in each scene.

Three scenes of data were selected for development of a single image that would serve as an agricultural data "mask". The agricultural mask image would permit analysis of ND data for those cells that included agricultural crops, compared to forests or other nonagricultural land uses. The mask image was developed from data acquired 16 May 1987, 26 and 27 June 1987, and 16 April 1988. Data above specified ND thresholds for the early season (16 April and 16 May) scenes were considered non-agricultural vegetation as most agricultural crops planted within the region are not yet emerged at this time. Individual cells with ND values above the specific thresholds were defined as forests or non-agricultural vegetation. Individual cells with ND values less than a specific threshold were defined as water. The 26 and 27 June scenes were composited to create a single image and used to identify those regions of vegetation, compared to urban or water areas. All cells with ND values greater than a specified threshold were defined as vegetation. The classified image from the 26 and 27 June scene was compared to the 16 May 1987 and 16 April 1988 scenes to determine the cells with agricultural, compared to nonagricultural, vegetation.

The agricultural mask image was applied to the individual registered scenes of visible, near-IR, and ND data in combination with an image that defined the counties within the study region. Visible, near-IR, and ND data in cells defined as "agricultural" by the agricultural mask image, and that were not defined as cloud contaminated by visible and near-IR thresholds, were utilized in computation of county statistics. The mean, standard deviation, maximum, and minimum values for the ND, as well as visible and near-IR data, were computed for each county in the study region. Seasonally integrated values of the mean county ND values for the June through August portion of the two years included in this study and were evaluated with similarly integrated climatic data and crop yield information, initially for six counties in Indiana.

Crop Model Analyses

The crop simulation model CERES-Maize (Jones and Kiniry 1986) was utilized to compute a crop moisture stress term for comparison with the satellite derived ND data and actual crop yields (USDA, 1988; USDA, 1989). The inputs required for the simulation model included daily precipitation, maximum and minimum temperature, total incident solar radiation, estimates of soil water holding capacity at several layers, and several variables that specify the characteristics of the management practices.

The crop model was utilized for six counties in Indiana selected for evaluation (Table 1). The counties were selected such that each county was within a different USDA Crop Reporting District. Temperature and precipitation data utilized in the simulation were selected from one observation location per county (Table 1).

Table 1. Indiana counties and weather observation locations utilized in crop simulation analysis.

County	Weather Station
Jasper	Rensselaer
Marshall	Plymouth
Adams	Berne
Montgomery	Crawfordsville
Grant	Marion 2N
Henry	New Castle

Solar radiation data were estimated for each county from the observed precipitation data (Richardson and Wright, 1984). Representative soil profile data were acquired for each county (Fuchs, et al. 1986) and used to derive soil water holding capacity information (J.T. Ritchie, 1988, personal communication) required as input to the simulation model.

Variables estimated by the simulation model included plant evapotranspiration (ET) and potential ET (PET), which were used to compute a moisture stress index (ET/PET). The simulation model estimates of ET/PET were compared with the county satellite-derived information as indicators of crop conditions.

RESULTS AND DISCUSSION

One assumption in the described methodology was that the variety of different agricultural crops observed by the satellite sensors respond similarly to drought conditions. Most of the land included in the analyses is utilized for non-irrigated agriculture and the analyses did include an attempt to further differentiate between agricultural and nonagricultural regions. Thus, the vegetation within the region was anticipated to respond to the significantly lower precipitation amounts of 1988 compared to 1987.

The lower amounts of precipitation and moisture deficiencies in 1988 compared to 1987 are evident in the time-series plots of county averages of the satellite derived ND vegetation index (Figure 2a). The June through August cumulative value of ND for Montgomery Co. Indiana was 42.3 in 1987 compared to 35.17 in 1988 (Table 2). Observed precipitation in the county was also greater in 1987 (44.56 cm) compared to 1988 (15.65 cm).

Table 2. June through August cumulative precipitation, stress index (ET/PET), ND vegetation index, and county maize grain yields for 1987 and 1988.

		June through August			maize
year	county	precipitation (cm)	ET/PET	ND	grain yield (bu/acre)
1987	Jasper	30.63	81.40	40.62	134
	Marshall	29.05	80.48	40.89	126
	Adams	36.85	88.78	41.28	133
	Montgomery	44.56	89.72	42.30	147
	Grant	37.17	89.78	41.39	147
	Henry	32.44	90.12	37.50	136
1988	Jasper	7.91	45.67	31.05	62
	Marshall	28.42	81.93	35.62	88
	Adams	17.15	62.59	25.33	85
	Montgomery	15.65	62.44	35.17	84
	Grant	16.66	65.45	30.02	94
	Henry	14.20	60.73	33.02	76

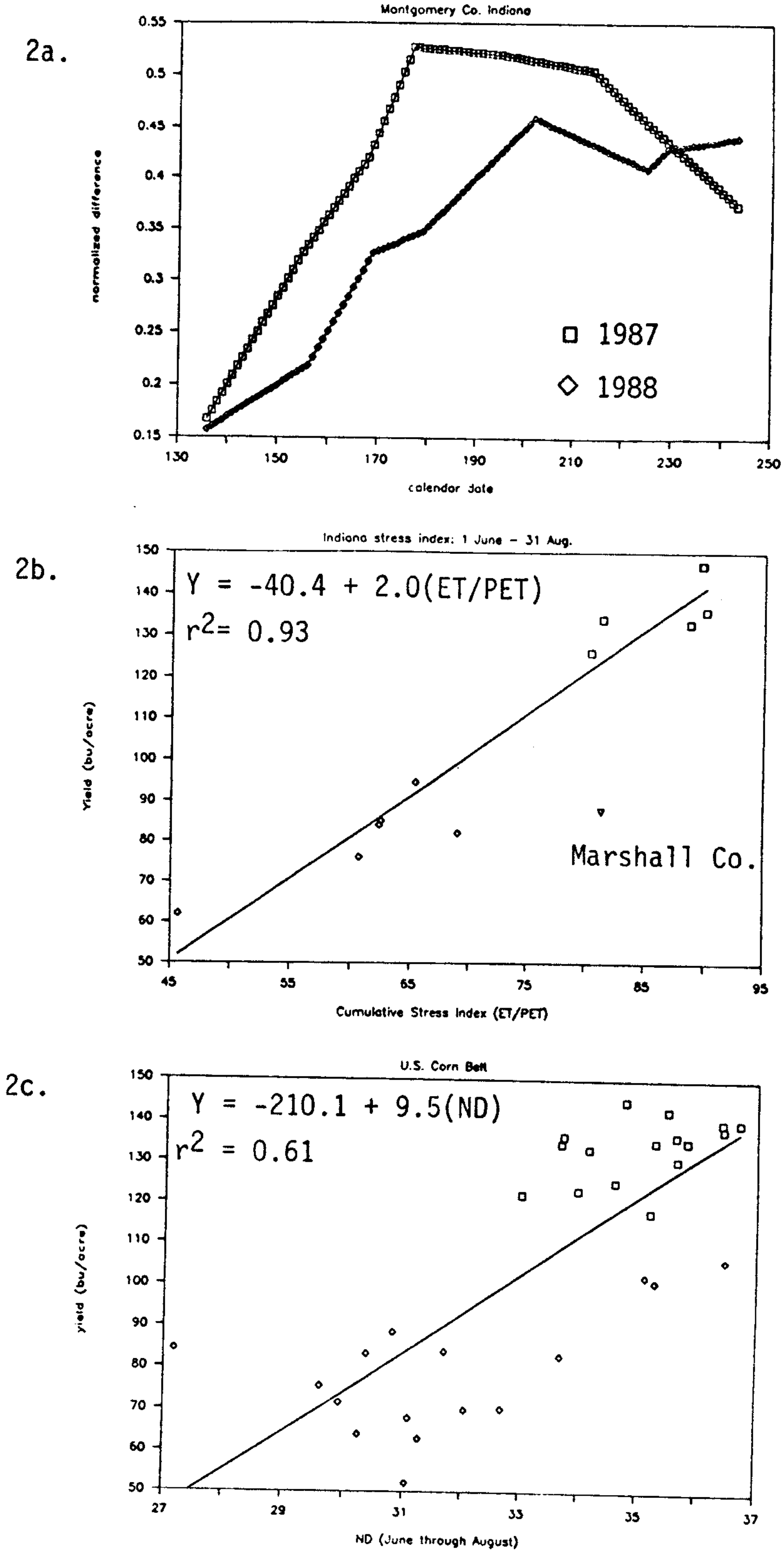

Figure 2. (a) 1987 and 1988 ND values for Montgomery Co. IN, (b) 1987 and 1988 maize yields and stress index for six IN counties, (c) 1987 and 1988 maize yields and ND for 16 Crop Reporting Districts.

The relationship between maize grain yield and the stress index was nearly linear. Marshall Co., however, exhibited nearly twice the precipitation as the other counties during the June through August interval in 1988. The stress index was also greater (larger values of the index are associated with less crop moisture stress), while the cumulative ND for the same interval appeared similar to other county data. The Marshall County results point out the value of more than one source of data and information. The observed precipitation for Marshall Co. in 1988, and thus the derived modeled estimates of stress, were similar to the values of 1987 (Table 2). The observed yields, however, were 38 bu/acre less in 1988 than 1987. The Marshall Co. anomaly was due to the use of a single weather station to estimate county-wide precipitation. The ND data, a sample of all 1 km cells (identified as utilized for agriculture), better represented the decrease in green vegetation in 1988 compared to 1987 in Marshall Co. (Table 2). Rainfall observed at a weather station (Warsaw) in a county adjacent to Marshall (Kosciusko) was 18.6 cm for the June through August interval and the computed stress index was 69.03.

The stress index (ET/PET) was associated with more of the variation observed in crop yield than the ND index (Table 2), however, less than the cumulative precipitation. When Kosciusko Co. data were utilized rather than Marshall Co. data for 1988 the r^2 value of the stress index increased to 0.93 (Figure 2b). The ND vegetation index was associated with greater than 60% of the variation in the stress index and precipitation observed in the June through August interval (Table 3).

Table 3. Results of analyses of seasonally cumulated climatic and ND vegetation index variables and final maize grain yields (n=12).

variables analyzed			
dependent	independent	RMSE	r^2
yield (bu/acre)	precipitation	11.9	0.86
yield	ET/PET	13.2	0.83
yield	ND	17.9	0.69
precipitation (cm)	ND	6.6	0.69
ET/PET	ND	9.4	0.63

These results were similar to results for 16 "Corn Belt" Crop Reporting Districts in Indiana, Illinois, and Iowa. The ND vegetation index, computed from a 15 km resolution global product (NOAA, 1990; Ohring et al., 1989; Tarpley et al., 1984) was analyzed during the June through August interval similar to the

Indiana county analyses. Weekly climatic variables were computed by the Climate Analysis Center (Motha and Heddinghaus, 1986). The cumulative ND (Figure 2c), precipitation (not shown) and ET/PET (not shown) were all associated with greater than 60% of the variation in observed maize yields.

In summary, the use of satellite derived climatic or crop related indices appear useful as supplements to traditional, ground observed information. The greatest use of the satellite observed data, however, might be to verify the spatial application of ground observations, which for this study were limited to one observation that represented the information for an entire county.

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DYNAMIC SPATIAL MODELS AND ARTIFICIAL WORLDS: A PERSPECTIVE ON ADVANCES IN GIS MODELING INTO THE 21st CENTURY

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ABSTRACT

The use and popularity of Geographic Information Systems (GIS) has radically increased over the last decade and ultimately changed our perspective of environmental planning and the world around us. Traditional modeling approaches however provide only a static representation or effectively a time slice view of the situation. In addition, a large percentage of the knowledge inherent in a real physical/biological system is dependent upon the spatial association of the system components. To predict dynamic changes over time within an ecosystem, models need to maintain the spatial relationships found within ecosystems, and they must adequately model and incorporate animal or human behavior. This paper describes a new approach to modeling animal and human behavior in the context of actual environments referred to as an "Intelligent Action Model". The Intelligent Action Model for this type of simulation is controlled by a hierarchical neural network which provides both primal motivations and adaptive learning. The intelligent action models are created by linking animal behavior into existing dynamic physical models through a genetic algorithm classifier system and a simulation tool referred to as PROMAP. Models developed under this framework will provide new research tools for modeling a wide range of environmental problems such as fire, hydrology, pest management, wildlife behavior, and human perception. These techniques will undoubtedly lead us well into the 21st century for modeling and simulating spatial dynamic processes of natural systems.

THE PROBLEM OF MODELING ECOSYSTEMS

While a tremendous amount of research over the years has focused on modeling ecosystem processes, very little has successfully achieved this task. This is due in part to the immensity of the data bases required for adequate description of the system under investigation and sophisticated data management systems for searching, assessing and manipulating such data. In addition, the transition functions used in the model must be able to handle spatially oriented data and provide a number of spatially oriented solutions.

This paper describes a framework being developed for building spatial dynamic models of natural processes in which an essentially unlimited number of environmental variables can be used to describe actual geographic areas. Problems associated with large data sets, as well as the need for hierarchical interactions have been addressed through the incorporation of various aspects of artificial intelligence. The work described here is an ongoing project and certain aspects such as the artificial intelligence components are still being developed. Deterministic spatial dynamic models are already being implemented and this paper will provide a background on how these models are designed. In addition, we lay out the work in progress as an indication of the potential of this type of modeling for researchers in other fields.

In the following sections we will outline how the environment is described; how single processes and multiple processes can be handled; how hierarchical interactions can be incorporated; and how it will be possible to include the influence of animal behavior into the models.

TRADITIONAL APPROACHES TO GIS MODELING

An ecosystem is a collection of interacting elements that together make up what is called the landscape mosaic. Not only are the component elements important, but also their arrangement within the mosaic. Data bases which describe this mosaic can be found in what are called geographic information systems or GIS.

Burroughs (1986) describes geographic information systems as"... computer based tools designed to collect, store, retrieve and change at will, manipulate, and display spatial information from the real world for a particular set of purposes." A GIS describes objects from the real world in terms of: Their position with respect to a known coordinate system; Their attributes, such as elevation and soil type, that are unrelated to position; Their spatial interrelationships with each other (topological relations), which describe how they are linked together or how it is possible to travel between them.

A GIS consists of several layers or maps, each of which describes the spatial distribution of some attribute, such as vegetation. The data bases can describe an area less than a square meter, or greater than several hundred square kilometers depending on the intended analysis. By the use of appropriate operators within the GIS program, questions related to the area described by the data base can be answered. These questions usually take the form of a suitability analysis which is the intersection of a given set of criteria within the data base. Each intersection indicates geographical location which meets the defined criteria.

The amount of information contained in a GIS is limited only by system storage capacity and the availability of attribute data. Storage requirements increase with increasing resolution of the data. An adequate GIS data base would allow the researcher to investigate for example, how changes in vegetation cover would effect the sedimentation rate of a local stream. This type of inquiry would require that information be passed across the data matrix in a manner consistent with known processes. Describing processes as spatial transitions imposes restrictions on the data storage method used in the GIS.

In vector systems the information about attributes is stored as polygons described by connecting nodes. In raster systems the information in each cell of a matrix describes the attribute for that geographical location. Processes are described as effects within neighborhoods and vector based GIS is not suited to neighborhood analysis. For that reason, raster data bases are used in this framework.

DYNAMIC MODELING USING SPATIAL DATA BASES

While GIS is an excellent means of depicting the environment, much of the applied research to this point have been simple suitability analysis, using a limited set of variables and map themes. While this approach to modeling environmental relationships certainly has some utility for a variety of applications for both local and regional government, it none the less is static representation of the environment or in effect, one slice in time.

For a model to simulate a natural ecosystem it must first be able to represent spatial attributes found in actual landscape (structure). Second, the model must be able to handle the flow of objects within the landscape (function). Third the model must be dynamic rather than static (change). Fourth, the model must allow evolution through adaptation. Each criterion links together to form the hierarchical structure that is necessary to complete the model.

The problem from a modeling standpoint becomes a matter of cellular interactions describing both the transitions between cells for a single process and hierarchical interactions.

Take for example a water runoff problem. Sediment transport between cells representing a watershed will result in transformation of the topography of the watershed over time. This is the result of a local action causing a global change. Describing water runoff over portion of the terrain within a cellular neighborhood will require identifying which areas are downhill, what are the soil characteristics and, what kind of vegetation cover is in each of the cells. Although this is an over simplified list it does point out the potential complexity of the appropriate algorithms. One factor that does provide a bit of simplification is the recognition that most processes can be described as cellular transition rules within the nine cell neighborhood. The process can be extended to larger areas by using the neighborhood as a moving window.

Two other similar problems within this watershed could be the reforestation of a watershed which would reduce the amount of runoff and therefore the total amount of sediment at the exit point of the watershed. The result of a local action causing a global change. Fire burns off the reforested area followed by heavy rainfall results in increased erosion and increased sedimentation at the exit of the watershed. The result of multiple process interaction causing both global (erosion effects hillslope profiles) and local (formation of channels and sediment buildup) changes.

While these may appear to be fairly simple problems on the surface, they are enormous complexity when viewed from a dynamic modeling perspective.

Attempts to use existing GIS programs to model spatial dynamic processes (Wilke and Finn 1988) have shown that the approach has promise but also problems. GIS programs were never intended to be used for this type of modeling. The algorithms used in the GIS operators were not designed for iterative processes, and in most cases are integer based. For this reason, researchers have devised specialized programs to work in cellular data bases. Most attempts have generally simplified the complexity of the environment (e.g. a lack of topographic data or other attributes) or the complexity of the algorithms (e.g. no diagonal transitions between cells for the sake of programming simplicity).

An alternative solution has been proposed by Sarennma et al. (1988) using an object oriented approach. The model developed is intended to describe the behavior of animals in natural habitats. The model obtained from aerial photographs, is classified into objects. The classification approach reduces the spatial information available to the system by combining areas of similarity into single homogeneous regions. Although all cell based systems assume uniformity within any particular cell, classification results in non-uniform sizes of regions. In addition, once within an object (e.g. a forest area), exact location can no longer be determined, and pathways between objects are predetermined and are not the result of actual terrain or other natural factors. This approach suffers from problems similar to those mentioned earlier in attempts to use GIS operators.

PROMAP SIMULATION SYSTEM AS A RESEARCH TOOL FOR SPATIAL DYNAMIC MODELING

To overcome the limitations imposed by existing GIS programs and the arbitrary constraints imposed by other researchers, Ball (1990) designed and authored PROMAP. PROMAP is a research tool that allows the construction of spatial dynamic models using the data bases of raster GIS. It is a real number system with algorithms designed for iterative processing.

As an example of the capabilities of PROMAP, Ball (1990) implemented a model of surface fire spread originally designed by Vasconcelos (1988). The new version of the FIREMAP model was able to approximate the shape of a surface fire under specified conditions without initializing templates. Although work continues on the improvement of the FIREMAP model, it demonstrates that complex spatial models can be designed using this approach.

By adopting PROMAP as the means of manipulating the information in the data base, spatial dynamic models of complex processes can be developed. As with other spatial models, two problems still exist even in the models developed under this system: the lack of multiple pathways of action and; the lack of true hierarchical interaction.

The lack of multiple pathways is not merely an IF/ELSE situation. In natural processes, under certain conditions, two or more choices of action might each result in an acceptable solution. The ideal model would, over several starts, give approximately the same answer but very rarely the exact same answer. To achieve this type of model response, cellular transitions should derive actions based on current environmental parameters. <u>A possible solution to the multiple pathway problem can be found in hierarchy theory</u>.

A SOLUTION TO THE HIERARCHICAL STRUCTURE PROBLEM

A mechanism to allow hierarchical interaction within the model may be found in the work of John Holland. Holland, et.al. (1989) address the problem of levels of approximation in describing systems. They state that "...given the complexity of realistic environments and the limitations of realistic [modeling] systems, it is unreasonable to expect...models to be isomorphisms in which each unique state of the world maps onto a unique state in the model" (Holland, et.al.,1989, page 31). In their book, they consider the design of a layered set of transition functions which they call a quasi-homomorphism or simply a q-morphism.

The q-morphism is the mapping of many attributes in the real system through a hierarchical set of transition functions in the model. <u>The adoption of Holland's q-morphic approach would satisfy both the requirements of hierarchical structure and multiple pathways</u>. Linking the q-morphic approach with PROMAP could be accomplished through the use of two types of artificial intelligence techniques: neural networks and genetic algorithms.

Various artificial intelligence techniques have been developed over the years that attempt to solve aspects of learning dealing with pattern recognition, decision analysis, and optimization. Two areas that are relevant to the framework being discussed in this paper deal with data filtering and optimization of coordinated activity. Data filtering has been examined using artificial neural networks. For a basic understanding of neural nets the see (Wasserman, 1989).

THE HYPOTHETICAL STRUCTURE FOR THE INTELLIGENT ACTION OPERATOR IN THE PROMAP SYSTEM

To solve the problems of a lack of hierarchical structure, multiple pathways and adaptation, a new PROMAP operator has been conceived that incorporates intelligence as part of the operator's basic algorithm. This intelligent operator has been designed which is composed of two types of artificial intelligence techniques: neural networks and genetic algorithms.

The learning ability inherent in neural network technology enable the intelligent operator to examine and obtain data from multiple "sensors" and supply a set of weighted values that describe the current environmental conditions and biophysical content in a more concise manner. The action of neural networks is more than a simple recoding scheme. Nets must be constructed and trained for specific tasks and therefore the framework consists of multiple networks. The need for such complexity of data filtering is easily seen when the amount of data contained in a GIS structure is considered.

In much the same way that humans ignore (or suppress) much of the information around them on a routine basis, that is non-essential, good models which have access to huge amounts of data need to disregard information which is not relevant to the current problem. In addition, the information which is relevant should dictate a flow-of-control strategy derived, perhaps, from an ancillary knowledge base. One method of handling both these factors is through neural network architectures.

Within the structure of the model there are two levels of environmental information. First is the level of the global system. At this level the model is concerned with general conditions such as mean temperature. Variables that change gradually may appear static and generally effect the model at very large scales. On the other hand, the second or local level may change quickly, be influenced by global conditions, or be effected by neighboring events. Actions that are occurring on the local level need to have information which is relevant at the neighborhood scale. Neural networks are included to provide this type of information in a manner consistent with the requirements of the model. By accepting information supplied by specialized operators within PROMAP, the neural net would then return the filtered data to other operators within PROMAP.

Using neural nets as the primary control structure allows simultaneous multiple processes. The neural network would schedule certain types of events ahead of others based on a precedence level system. Simply, global actions need to occur prior to local changes (it should rain before a water runoff simulation is activated). Once the environmental information has been processed it must illicit some type of action. Action in the context of the model may simply be a change in temperature or perhaps the loss of trees due to fire. This implies the possibility of multiple actions and in a dynamic environment this may mean action based on data from multiple, possibly conflicting, inputs. Dealing with this situation in the modeling framework is the domain of the second use of artificial intelligence techniques: classifier systems which incorporate adaptive learning. These systems derive their power from the use of genetic algorithms.

Genetic algorithms (GA) are algorithms based on the mechanics of natural selection and natural genetics. GA have been shown to be effective in the areas of machine learning, search, and optimization strategies (Goldberg, 1989). In the complex spatial models being designed under this framework, all three areas are important.

GA provide a robust methodology for restricting the search for a "best" choice of action to those possibilities with the greatest potential for success. Success in this context should be thought of as a solution which results in an action consistent with some expected outcome. This does not imply an optimal solution, only that the simulated process behaves in a manner that would be observed in nature.

GA uses a population of "strings" that are used to examine current environmental conditions and arrive at some solution (action). Strings can be envisioned as chromosomes, and strings that provide better solutions are retained in the population at a rate according to a payoff scheme (fitness). To keep highly fit strings from overwhelming the population, natural genetic functions of crossover and mutation maintain variation within the population. The string population acts as the memory for the specific action that is being evaluated. If the component is capable of learning from its past attempts, the total system gains new knowledge.

A process may (and usually does) consist of multiple actions. A model could code an entire set of actions associated with a process into a single function, which is generally the accepted strategy of most modeling schemes. The drawback is the need to determine, apriori, what actions are to be done and under what conditions. This is the approach used with rule based systems and the weak point is known as the uniqueness factor.

For rule based systems to function, an assumption is made that all knowledge of the system is complete. If the model encounters a unique situation it fails. Real-time action in a dynamic environment virtually guarantees that situations will be encountered that have not been anticipated by the designer. It is this type of situation that GA provides an effective solution. Individual components are capable of adapting, allows them to respond to unique situations by making a "best guess". By dividing the process into smaller components, it only becomes necessary to activate the required components to achieve the desired actions.

Through the use of a "tag" system, the component operators can be triggered as needed through what is termed spreading activation. The component operators that have been activated invoke the needed hierarchical response within the model and the system.

IMPLICATIONS OF APPLYING THIS FRAMEWORK FOR MODELING NATURAL PROCESSES

The framework as described in this paper offers the researcher interested in ecological processes several advantages. First is the capability of using data bases which reflect real-world environments and have the potential for being tested. Building a model of an ecosystem process and running it in the laboratory is of no benefit unless the model can be tested against the real system. Some natural processes take too long in nature to be useful, but others are easily available to testing. The FIREMAP model is ready for field testing and can be applied to prescribed burns or to examine historical fires. Application of this framework for examining hillslope evolution due to water runoff as well as defining transitions between sheet flow and rill formation are under development. Other areas of potential investigation are population dynamics involving fluctuations in genes.

Second, this framework also provides the possibility for simulating animal behavior in complex natural environments. Along these lines, Wilson (1986) developed an artificial animal model (ANIMAT) acting in a simulated environment containing food and other objects. The environment was represented by a two dimensional array of hexagonal cells which were labeled as trees, food or, vacant. The ANIMAT's task was to explore its 18 by 58 cell environment consisting of woods and open space, finding food and avoiding trees. According to Wilson (1986) the ANIMAT's basic problem was "the generation of rules which associated sensory signals with appropriate actions so as to achieve the optimization [of the rate of occurrence of environmental signals]." Wilson's intelligent performance and adaptation algorithms are examples of the use of genetic algorithms. The cell based environment that Wilson uses translates directly to the structure used in the framework described in this paper.

Third, the framework also provides the ability to work with entirely synthetic environments or artificial worlds of any predetermined complexity. This aids the investigator by allowing algorithms to be tested under conditions for which the outcome is predictable. Being able to validate the function of individual components makes it much easier to validate the overall model.

STATUS OF CURRENT RESEARCH IN THE DEVELOPMENT OF THIS STRUCTURE

Work has continued using the PROMAP system to develop dynamic models. Currently, four models are under development. They are: Fire Behavior, Hillslope Evolution, Forest Succession and Hiker Behavior models. While these models provide an opportunity to test the viability of dynamic spatial models, as of yet the intelligent action component has not been fully incorporated.

Two projects are currently underway to examine the viability of neural nets and genetic algorithms before they are structured into the intelligent operator, described above. A pilot study is underway to develop a neural network prototype decision support system for forest management applications. In addition, genetic algorithms are being incorporated into an artificial animal project in conjunction with the Ecology and Evolutionary Biology department at the University of Arizona for research and exploration of artificial biological specimens. Both of these projects will provide a basis for the development of the intelligent operator as described earlier in this paper.

CONCLUSION

The advantages of being able to use data bases that describe large scale, actual environments opens the door for producing models that can be applied to real problems. The spatial dynamic modeling that is described in this paper is not meant to replace the traditional mathematical models. What is presented here is an alternative that can be used to design and test ecosystem models in real world environments.

The model of surface fire can be tested under actual conditions to determine how well the model can predict the spread of the fire. In addition, the model can be applied to any area that has been mapped into a GIS data base. As the framework progresses, the inclusion of the artificial intelligence components will extend the modeling into multiple processes. Although some processes such as forest succession would not be testable, the ability to examine the potential effects of fire, rain, grazing and other perturbations in various intensities, would provide more insight into process interaction.

The ability to access existing data bases allows the modeler to enter the investigation of complex systems through the use of tools such as the framework described in this paper. Although this is a different approach than traditional modeling, it provides not only a means of examining ecosystem processes, but also of extending the usefulness of the models from research to application. This approach will undoubtedly lead us well into the 21st century for modeling and simulating spatial dynamic processes of natural systems.

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PREDICTING IMPACTS OF SEA LEVEL RISE WITH A GIS-BASED SIMULATION MODEL

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ABSTRACT

Twenty percent of the contiguous United States coast was mapped and simulated using Landsat MSS data, digitized elevational data, and a simulation model. Ninety-three sites from Maine to Washington were analyzed for various scenarios of sea level rise due to the greenhouse effect. In the absence of ground truth based on field checking, National High Altitude Photographs and National Wetland Inventory maps were used to confirm interpretations. A rule-based model was developed to predict responses of wetlands and lowlands to inundation and erosion. To facilitate and improve the image processing, digitization of elevations, and analysis and display of results, the model is being coupled to ERDAS and ARC/INFO.

KEY TERMS: coastal wetlands; global warming; sea level rise; model; GIS.

INTRODUCTION

An accelerated rise in sea level due to global warming would have a serious impact on the distribution of U.S. coastal wetlands. Salt, brackish, and fresh marshes as well as mangrove and other swamps would be lost due to inundation and erosion, or would migrate inland as adjacent lowlands not protected by engineering structures are inundated. The value of these wetlands as habitat for wildlife would be impaired, and their biodiversity would decrease.

In a previous study, Holcomb Research Institute developed a simulation model (SLAMM) that was used to conduct preliminary regional analyses of the effects of sea level rise on U.S. coastal wetlands. The original model was based on manually coded data on elevation and cover classes from topographic maps, using a one km^2 grid (Park et al. 1986a, 1986b, Armentano et al. 1988). Simulations suggested that large areas of coastal wetlands would be lost with sea level rise. However, both data and the model needed refining if the results were to be used for evaluating policy. A more recent study has used remotely sensed data and more refined modeling procedures to obtain improved estimates of how much of the nation's coastal wetlands and lowlands are likely to be lost under various scenarios of sea level rise. The study is described in more detail in two reports by Park et al. (1989a and 1989b).

METHODS

DATA

Ninety-three sites were chosen, using an unbiased systematic sampling of U.S. Geological Survey topographic maps at a scale of 1:24,000. (Two sites are represented by 1:64,000 maps and two by 1:25,000 maps.) These sites represent twenty percent of the coast of the contiguous United States and provide reasonable coverage for any particular coastal area (Fig. 1). Four supplemental sites were also chosen for verification purposes. For most coastal sites with low slopes and extensive lowland and wetland areas, a cell size of 500 m by 500 m was used; this is an area of 25 hectares (ha) or 61.75 acres; with this coarse-grained resolution a site typically contained four quadrangles. For sites with steep slopes or heterogeneous urban development, a fine-grained resolution of 250 m by 250 m (6.25 ha or 15.44 acres) was used; normally such a site was restricted to one quadrangle. A normal coarse-grained site contains as many as 3400 cells; some sites with fine-grained resolution and covering four quadrangles contain almost 14,000 cells.

Each cell is represented by information on elevation, percent cover in various classes, development, and presence of protective engineering structures. Eleven cover classes were distinguished, including upland (above 12 ft or 3.66 m elevation); lowland (above mean high water spring tide level [MHWS] and below 3.66 m elevation); sandy area (usually backshore and dunes areas, but including both lowland and upland areas characterized by exposed sand); freshwater marshes, saltmarshes, freshwater swamps, mangrove swamps, combined beaches and tidal flats, rocky intertidal areas, and water.

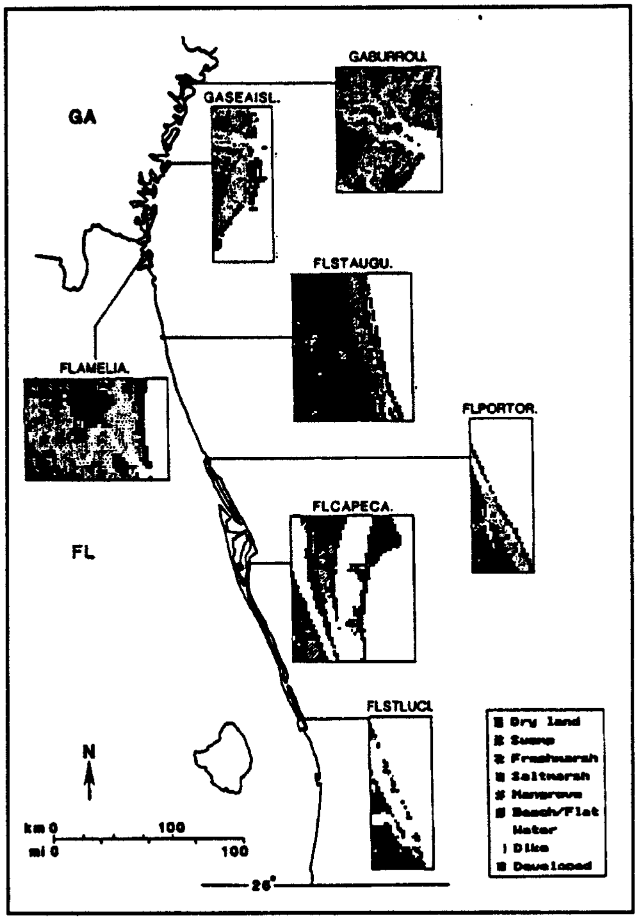


Figure 1. South Atlantic sample sites.

Cover Classes

The cover-class data were obtained by analysis of Landsat MSS data from essentially cloud-free, geocorrected scenes, augmented by visual interpretation of high-altitude color-infrared photographs (with a scale of 1:58,000). Numerous studies have shown that these forms of remote sensing can effectively differentiate wetland and other coastal cover types (Estes and Thorley 1983).

Well established methods for quantifying remotely sensed cover-class data were used (Mausel 1985). The HINDU algorithm (Dasarthy 1974) was used to partition the spectral data into classes of repetitive signatures for a particular site. Usually 20 to 30 clusters were obtained. These were combined by an experienced analyst to represent the cover classes on the basis of cluster statistics and spectral signatures, confirmed by information from the maps and photographs. The correspondence between pixels in combined clusters and a designated cover class, such as low marsh, is not perfect. Preliminary analyses of selected sites suggest that accuracies for well defined classes range from 75 to 95+ percent. Features represented by mixed pixels or by ambiguous spectral responses pose a problem. Residential and commercial developments were not identified from the spectral data because pavement and roofs could be confused with the "sandy area" class. However, because of the need to identify all wetlands, the swamp class was used despite an ambiguous signature. Where possible, high and low marshes were distinguished, based on "dry" and "wet" spectral signatures.

Each Landsat pixel represents an area 57 m by 79 m. The data were resampled and aggregated to form pixels with an area of 71 m by 63 m, and were printed at a scale of 1:24,000 to facilitate comparison with topographic maps. Thus with a 500-m by 500-m grid, the unit cell contains 55+ pixels. The percent cover for each class was stored and reported in increments of 5%.

In the absence of "ground truth" based on detailed field checking, the cover determinations for any particular site should be considered best-estimates consistent with the regional goals of the study. Topographic maps and USFWS National Wetland Inventory (NWI) maps were used to confirm the interpretations. Because the Landsat imagery is often from 1986 and 1987 and supersedes map coverage by a significant number of years, the spectral signatures were often accepted in the event of conflict. For example, at a New Jersey site both the topographic map, photorevised in 1972, and the NWI map, based on 1977 aerial photography, showed an extensive unbroken marsh; however, the Landsat imagery and the high-altitude photograph provided unmistakable evidence that a large area had been converted to lowland (probably with dredge fill).

An earlier report (Park et al. 1989a) was based on half the sites, and two regions (the West and Northeast Coasts) suffered from inadequate sample size. Since that report was written, the full sample comprising twenty percent of the contiguous coast was analyzed; in addition, errors were corrected in the site data and the model was improved slightly. The preliminary study underestimated the coastal wetlands of the Mid Atlantic and West Coasts when compared to NOAA estimates (Alexander et al. 1986). The larger sample size corrects the problem with the West Coast, but the Mid Atlantic wetlands are still significantly underestimated (Figure 2); this seems to be based on a differing concept of how far inland the Mid Atlantic estuaries should be sampled. Otherwise, there is reasonable agreement between our study and the more extensive NOAA study.

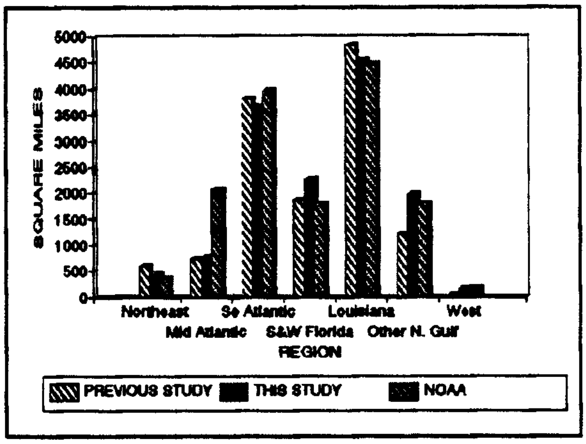


Figure 2. Regional comparison of present areas of coastal wetlands estimated with subsample of 46 sites (Park et al. 1989a), sample of 93 sites (Park et al. 1989b), and NOAA estimates (cf. Titus and Green 1989).

Development

Because of confusion with the "sandy area" spectral signature, residential and commercial developments were identified from topographic maps. If a cell contains sufficient buildings and other structures worthy of protection (including airports and wharves), the cell was characterized as developed. Because the maps are older than the Landsat data and the simulations start with the Landsat coverage, this underestimates the extent of development and subsequent protection. It would be of interest to simulate continued coastal development, and that is the subject of an impending study.

Elevations

The elevational data were obtained by digitizing the corner elevations of each cell, based on interpolations of elevations from the topographic maps. Both the elevational and the Landsat data were recorded using the Universal Transverse Mercator grid and were combined for each cell in the site data file. An elevational mosaic was assumed for saltwater wetlands, with each cover class traversing its full elevational range within a cell (representing the usual microtopography that occurs with small tidal flats and beaches, tidal creeks, natural levees, and back-levee areas). Saltwater wetland elevational ranges were computed by assuming constant relationships of the wetlands to tidal datums (cf. Lefor et al. 1987), with mean or half tide level (MTL) as 0; beach and tidal flats extending from mean low water (MLW) to mean high water (MHW), or from MLW to MTL on coasts with low wave energy and vegetated wetlands; low marsh extending from MTL to MHW; high marsh extending from MHW to MHWS; and mangrove swamps extending from MTL to MHWS. (Occasionally saltwater wetlands occur above MHWS, but the area is small and can be ignored.)

DESCRIPTION OF MODEL

The objective of the modeling was to simulate the dominant processes involved in vegetative wetland conversions and related shoreline reconfigurations during long-term sea-level rise. The model, SLAMM2, differs from other wetland models (Day et al. 1973, Wiegert et al. 1975, Hopkinson and Day 1977, Browder et al. 1985, Sklar et al. 1985, Costanza et al. 1987, 1990, Kana et al. 1988) by its ability to predict map distributions of wetland cover under conditions of accelerated sea level rise and by its applicability to the diverse wetlands of the contiguous coastal United States.

Eleven cover-classes were modeled in each of over 3,000 cells for 115 or more years for 10 scenarios for each of 97 sites (including 4 verification sites); therefore, the level of scientific detail represented had to be balanced with efficient computational algorithms. In essence, SLAMM is a knowledge-based simulation model that uses a complex decision tree and scalars to represent qualitative relationships. The basic constructs for each of the processes are organized in two sections, the inundation model and the map-based spatial model.

Inundation Model

The colonization of newly inundated dry land by wetland vegetation and loss of wetlands due to further inundation is based on a straightforward geometric relationship, with lag effects for some conversions. Six processes are considered as part of the inundation model:

- **Relative sea level change** based on the historic eustatic trend of 1.2 mm/yr, an exponential rise depending on the scenario chosen (Fig. 3), and the rate of local subsidence.

- **Conversions between classes** using a discrete, algebraic model with a time step of 5 to 25 years (depending on the rate of sea level rise) and alternative pathways of change, depending on site and cell conditions. Each class occurring in a cell is converted to another class for given conditions.

- **Change to subtropical conditions**— the SLAMM2 simulations assume that for all scenarios other than a continuation of the current sea-level trend, mangrove swamps can become established at shoreline sites in the northern Gulf of Mexico and Atlantic coast of Florida beginning in the year 2000. They are assumed to grow in Georgia and South Carolina at slightly later dates.

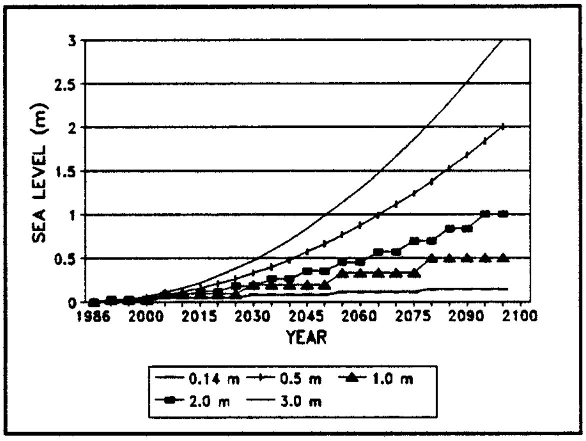


Figure 3. Sea level rise scenarios used in the study; the step-wise patterns indicate the longer time steps used for some scenarios.

- **Protection by coastal engineering structures**— the presence of dikes and levees completely enclosing coastal areas was noted from the topographic maps. The two protection scenarios represent further construction of dikes around all developed areas and all dry land, respectively. Areas so protected are not allowed to convert to other classes in the simulations. Enclosed wetlands are assumed to be maintained in their initial condition.

- **Death and colonization**— conversion of low marsh to water by inundation and corresponding conversion of high marsh to low marsh are assumed to occur within the period of a normal time step of five years or more. However, in the model, mangrove swamps are converted to water at the rate of 10% per year of the potential, producing a 50% lag for a time step of five years. Because they are intolerant to saltwater, freshwater swamps and marshes are converted instantaneously to water or high marsh, respectively, or to mangrove swamp if subtropical. Inundated lowlands and sandy areas are instantaneously converted to either high marsh or mangrove swamp by the model.

- **Sedimentation and accretion**— in deltaic areas characterized by extensive marshes, 10 mm/yr seems to be representative, although much higher maximal values have been observed; in many areas with moderately extensive wetlands, 5 mm/yr seems to be a common midrange value; in areas with little wetland development, 2 mm/yr seems to be a representative minimal value (cf. Armentano et al. 1988). Therefore, as a simplifying assumption, the initial percentage of salt wetlands at the start of the simulation was used as an indication of accretion rates, and one of these three values was used. Because marsh areas that are back from water courses tend to have accretion rates that are approximately half those of streamside marshes (cf. Gosselink 1984), the values are halved for high marsh. In a detailed study of a mangrove swamp in Australia, Bird (1986) reported rates varying from 2 to 13 mm/yr. We have assumed 5 mm/yr to be representative and have used that value for all areas with mangroves. If sedimentation exceeds sea level rise under any scenario, areas of very shallow sheltered water are converted to tidal flats which in turn are converted to wetlands.

Spatial Model

In addition to the effects of inundation represented by the simple geometric model described above, second-order effects occur due to changes in the spatial relationships among the coastal elements. Accordingly, SLAMM2 incorporates a map-based model component to consider five spatially important processes:

- **Erosion of wetlands**— under equilibrium conditions, erosion and deposition balance and wetlands are not lost. However, even historic sea level rise coupled with local subsidence has upset coastal equilibrium in many parts of the world (Bird 1986, Bruun 1986). Qualitative relationships are defined and used as thresholds for including constant rates of wave erosion in simulating the localized loss of wetlands. The effects of severe storms are included in these average values. The model can represent several levels of erosion based on the observed average fetch (the distance across which wind-driven waves can be formed) of sheltered water.

- **Exposure to Open Ocean**— the model also recognizes exposure to open ocean as triggering erosion of wetlands. Cells can become exposed as protective barrier islands and spits are breached. The model changes cells from unexposed to exposed if they are in line, based on prevailing wave direction, with exposed water and without intervening areas other than water.

- **Beach erosion**— Bruun (1962, 1986) has shown that on the average, recession of beaches and backshore areas is one hundred times the change in sea level. The model incorporates this relationship.

- **Overwash**— as erosion of backshore and dune areas occurs and as other lowlands are drowned, wetlands on the lee side of coastal barriers are subject to conversion due to overwash, the process by which sediments are carried over the crest of the barrier and deposited onto adjacent wetlands. This process is simulated only for areas having a beach and only during the time step in which the lowland is breached.

- **Erosion of sandy areas** is simulated to maintain equilibrium with adjacent beaches; but erosion of lowlands and uplands that do not have a multispectral signature indicating sand is not simulated. Therefore, recession of sandy areas is probably overestimated by the model, but erosion of other dry lands is ignored.

In summary, the model probably errs slightly toward maintenance of wetlands and toward accelerated loss of barrier islands, but overall it provides prudent forecasts useful in guiding policies for coping with sea level change.

SIMULATIONS AND SYNTHESIS OF RESULTS

As would be expected from the major differences in coastal physiography around the United States, the potential for loss of wetland resources due to a rise in sea level varies widely from region to region. Thus, balanced sampling was required for both the regional and national estimates of losses. Each of the 93 sites was chosen using an unbiased sampling procedure and covers an area from the open ocean to upland (or diked lowlands) so that both loss and migration of wetlands can be evaluated. These sites represent a broad spectrum of temperate and subtropical coastal types, with varying tidal ranges, subsidence and accretion rates, fetches, and degrees of development. The standard set of simulations for each site spans a period from the date of the remote imagery to the year 2100 and provides estimates of responses to various scenarios for sea level rise and for protection of dry land. The cover classes were aggregated for reporting purposes.

NATIONAL IMPACTS

The percent coverage of the coastline with these sites was used to estimate the initial area of wetlands, as well as the areas projected to be lost under the different sea-level scenarios. For example, the 17 sites in the South Atlantic region represent 20.14% of the area of the South Atlantic as defined in this study; the reciprocal of that value yields a transformation factor of 4.97, which was used to scale the subsample results to the entire South Atlantic. These calculations yield a national estimate of 13,891 mi^2 of coastal wetlands in the mid 1980s (the time of Landsat coverage for the respective sites), compared to the estimate of 14,723 for comparable wetlands as reported by Titus and Green (1989); the wetlands for the Mid-Atlantic are underestimated in this study.

In Figure 4 the independent variable, time, has been replaced by sea level, making the ordinate more general but causing it to be expressed on an exponential scale. Mindful of the nonlinearity, saltmarshes are seen to expand initially and then decline by approximately 2,000 mi^2 with a 0.1-m rise in sea level; this decline is due to the predicted rapid loss of saltmarshes in Louisiana and the rest of the northern Gulf of Mexico. With only developed areas protected, the decline of saltmarshes will be gradual and mangrove swamps will increase significantly. (With no protection, saltmarshes will decline less rapidly; and with protection of all dry land, saltmarshes will decline rapidly.) With a 1-m rise by the year 2100, and with all developed areas being protected from inundation, 6,629 mi^2 or approximately 48% of the coastal wetlands of the contiguous United States could be lost.

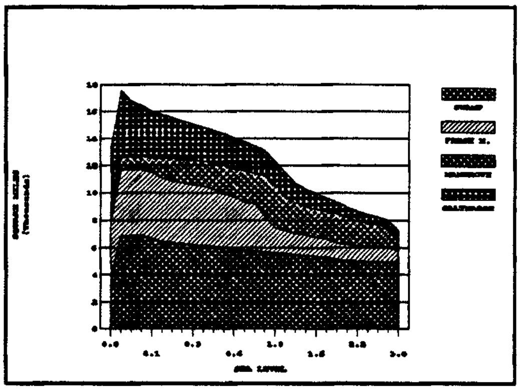


Figure 4. Changing areas of wetlands of the contiguous U.S. coast with global warming and with existing developed areas protected from sea level rise.

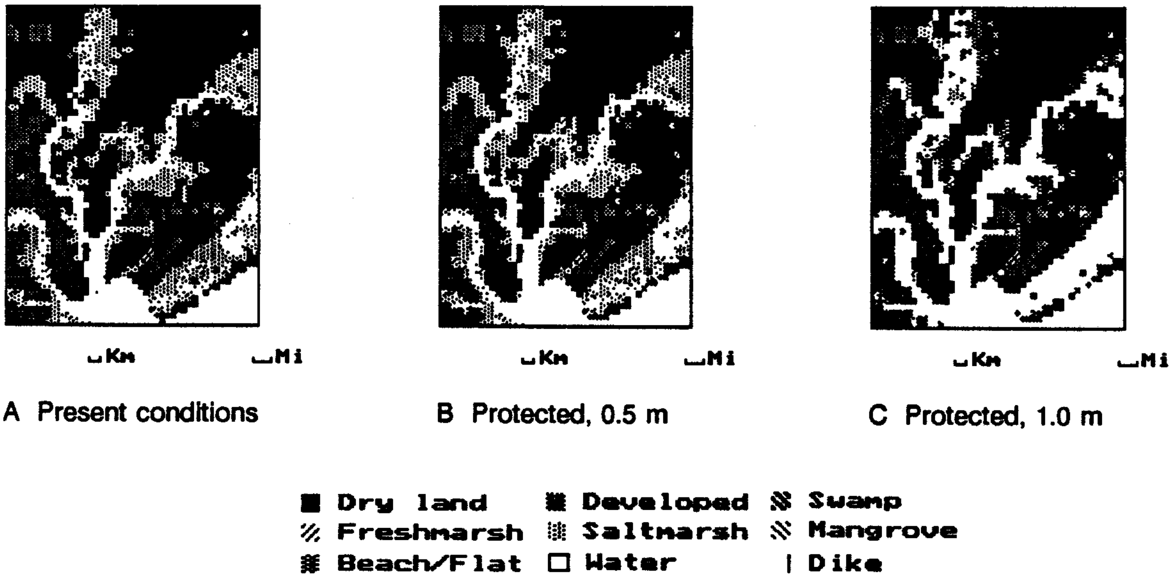
CASE STUDIES

Charleston, South Carolina

This historic town is at the confluence of several estuaries with large tidal ranges and extensive marshes. Sensitivity analysis indicates that the predicted response to sea level rise is based on changes in relative elevation and depth of water due to sedimentation, subsidence, and inundation. With a half-meter rise most of the saltmarshes would be inundated (Fig. 5B). The one-meter scenario yields an estimate of 47% loss of saltmarsh by 2075 (Fig. 5C), which is quite close to the estimate of 51% by 2075 reported by Kana et al. (1988), based on detailed transects.

St. Augustine, Florida

This area is characterized by modern and Pleistocene barrier island complexes, a high tidal range (1.67 m), and extensive fresh- and saltwater marshes. The simulation maps illustrate the importance of changing spatial relationships due to erosion (Fig. 6). The vegetated wetlands respond to sea level rise as a function of both inundation and erosion. Loss of the back-barrier marshes is accelerated when the narrow barrier islands are breached at about 1.4 m. Also, as the climate becomes warmer, mangroves replace the saltmarshes. Fractal dimensions of the the marsh-water interface were computed for this and other sites; the fractal dimension increases as marsh disintegration occurs; this suggests that increased habitat will be available briefly for shrimp and other estuarine fisheries.

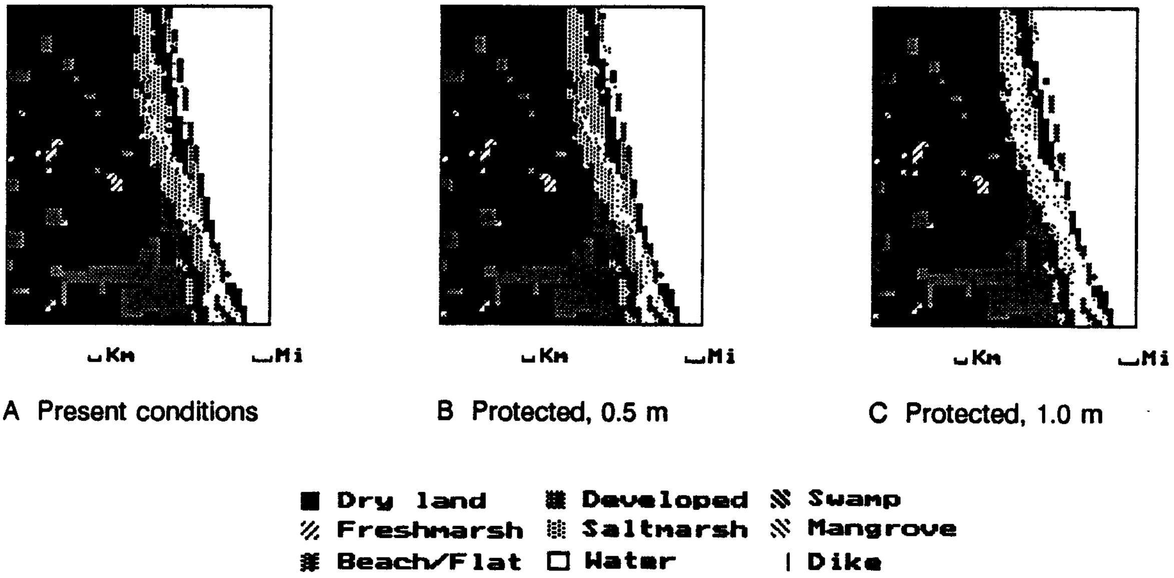


A Present conditions

B Protected, 0.5 m

C Protected, 1.0 m

Figure 5. Maps of the Charleston, South Carolina site showing initial conditions (A) and predicted conditions for the year 2100, with residential and commercial developments protected and with sea levels as indicated.



A Present conditions

B Protected, 0.5 m

C Protected, 1.0 m

Figure 6. Maps of the St. Augustine, Florida, site showing initial conditions (A) and predicted conditions for the year 2100, with residential and commercial developments protected and with sea levels as indicated.

CURRENT AND FUTURE DEVELOPMENTS

At present an integrated system is being developed, linking the new version SLAMM3, with two popular geographic information systems (Fig. 7). ERDAS and ARC/INFO systems are used for data input by generating cover information from satellite data and elevational data from USGS DEM or digitized contour data. Several programs were developed to manipulate the land-cover and elevation data to interface them with the simulation model SLAMM3. Those include a program for merging class information, for aggregating to a particular grid size, for assigning elevational data for each cover class within each cell, for interpolating contour data to generate discrete DEM data, and for data reformatting and file management.

SLAMM3 uses the cover classes and elevational data in raster form for simulation modelling of future sea-level rise effects. The simulated results are presented in several forms. The map of the simulated change on coastal wetlands is displayed, printed, and plotted either in raster or vector form using ERDAS image/graphic screens, black/white and color printers, and plotters. The descriptive tabular information generated from the simulation modelling can be exported as ASCII files to external database or spreadsheet programs such as dbase IV, Lotus 123, and Quattro.

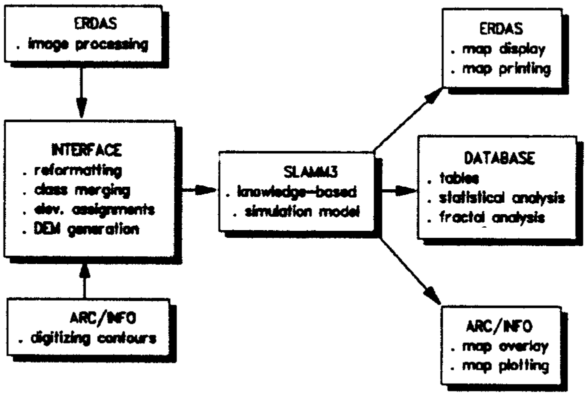


Figure 7. Linkage of the SLAMM simulation model and geographic information systems.

The simulation modelling of environmental processes could be the most powerful application of geographic information systems in future land and resource management (Parker, 1988). The integrated management of coastal ecosystems requires a great deal of information resulting from very complex and sometimes poorly defined processes. Modelling is one approach to deal with such complex systems (Dangermond, 1987). However, the modelling capacity of today's GIS is still superficial. The GIS itself is not sophisticated enough to perform the very complex spatial and temporal modelling to simulate dynamic changes of the coastal environment due to sea level rise. Sequential processing steps and continuous judgements for each of the complex processes are required to represent the changes to the ecosystem. By integrating the spatial analysis system with the SLAMM3 knowledge-based system, a more powerful and efficient analytical tool becomes available to project probable sea level rise effects on coastal wetlands. The role of GIS within the system is essential for data input, storage, manipulation and output report, and is a very efficient linkage between the modelling environment and various operational functions. Further refinement of the system will enable tax maps, positions of engineering structures, and flood and storm-surge data to be incorporated into the simulations.

ACKNOWLEDGMENT

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THE INDIANA DEPARTMENT OF NATURAL RESOURCES GEOGRAPHIC INFORMATION SYSTEM (IDNRGIS): CURRENT STATUS AND FUTURE APPLICATIONS

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The Indiana Department of Natural Resources acquired Geographic Information System (GIS) capability in April 1989, with the installation of ARC/INFO on a Prime 2755 mini-computer. The GIS was originally intended for the Fish and Wildlife Division to manage the National Wetland Inventory (NWI) for Indiana. Prior to installation of the hardware and software the GIS was upgraded to a departmental system and management was transferred to the Management Information Systems Division. A second installation is currently located at the Indiana Geological Survey Coal Section.

The mission of IDNRGIS is to serve as a tool and service for various divisions of the Department and to provide technical expertise to assist in the development of applications for our client divisions. To accomplish this mission, various generally available data sets were acquired in addition to NWI. In-house system use training is also available for department staff.

In addition to Prime, IDNRGIS includes two Tektronix 4209 graphic terminals, a Calcomp 1044GT 8 pen line plotter, a Calcomp 9100 Digitizer, and a 9600 baud modem for remote login. The facility at Geological Survey consists of pcARC/INFO on a IBM PS2 Model 80 and an additional pcARC/EDIT and Starter Kit attached to a IBM PS2 Model 55sx with a digitizer. The Survey facility includes a Kurta IS3 digitizer and a HP Draftmaster 1 plotter.

IDNRGIS currently contains the following data;

NATIONAL WETLAND INVENTORY for Indiana. The inventory consists of three layers for each 1:24,000 quadrangle map. These layers are polygon, line, and point. Each feature in the layer is identified by the US Fish and Wildlife Service wetland classification, see Cowardin and others (1979). Polygon features have a resolution of .25 acres.

DIGITAL ELEVATION MODELS (DEM). There are two sets of DEM data for Indiana, 1:24,000 and 1:250,000. Digital elevation models are USGS products and consist of a regular array of elevations referenced horizontally in the Universal Transverse Mercator (UTM) coordinate system. The spacing of elevation data in the 1:24,000 DEM is 30 meters and the elevation is recorded in meters. The vertical accuracy is plus or minus 7 meters (feature to mean sea level). The 1:250,000 DEM elevation data spacing is 3 arc-seconds (average of 71 meters in Indiana) and a vertical accuracy of plus or minus 30 meters (feature to mean sea level), U.S. Geological Survey (1987). IDNRGIS has full state coverage, with the exception of a small area in Posey County, for the 1:250,00 DEM, and 166 1:24,000 DEMs in the southwest part of the state .

LAND USE AND LAND COVER DIGITAL DATA. The data consist of land use and land cover, political units, hydrologic units, and census county subdivisions. The land use and land cover map is compiled to portray the level II categories of the Land Use and Land Cover classification system documented by Anderson and Others (1976). The associated maps portray either natural or administrative information. All maps are compiled on a scale of 1:250,000 and the land use and land cover map has a resolution of 4 hectares (10 acres) for Urban or Built-up Land, Water, Confined Feeding Operations, Other Agricultural Lands, Strip Mines, Quarries, and Gravel Operations, and Urban Transitional areas. All other classes of land use and land cover have a resolution of 16 hectares (40 acres), U.S. Geological Survey (1986). IDNRGIS has full state coverage, with the exception of a small area in Posey County for the Land Use and Land Cover data.

US BUREAU OF CENSUS, PRECENSUS TIGER/LINE FILES. TIGER (Topologically Integrated Geographically Encoded and Referencing), is a series of digital files, grouped by county, which are intended to assist government and business in utilizing the volume of information gathered during the 1990 Census. The TIGER/LINE files contain information on census tracts, census blocks, zip codes, transportation features, and hydrologic features. The transportation and hydrologic features were obtained from the USGS 1:100,000 digital line graphs (DLG) and the other features were added by Census Bureau. The scale of the TIGER data is 1:100,000, Bureau of the Census (1990). IDNRGIS has TIGER data for all 92 counties available.

Current activities mainly involve three Divisions -- Fish and Wildlife, Water, and Geological Survey. Fish and Wildlife activities are focused around NWI. County wetland summary maps and reports are currently being generated. NWI was used to prepare a wetland impact report for a proposed industrial site in southwest Indiana.

The Survey Section of Division of Water is currently using IDNRGIS. The Section recently acquired computerized survey instruments and is using GIS to develop plots of conducted surveys. In addition, the Division has been working with consultants which conduct photogrammetry work for floodway mapping to provide digital as well as cartographic products.

The Geological Survey facility is currently developing the Indiana Coal Mine Information System, which contains information pertaining to lands mined for coal prior to August 3, 1977 and are inventoried by the Division of Reclamation and US Office of Surface Mining Reclamation and Enforcement. The database will assist the Restoration Section of Reclamation in developing alternative reclamation plans. The database may be expanded in the future to include additional mines which were active from August 3, 1977 to present. The Geological Survey Drafting Section also utilizes AutoCad for preparation of maps, some of which have been converted into pcARC/INFO.

Several Divisions are currently studying possible application of GIS technology. Fish and Wildlife personnel are developing a database for Glendale Fish and Wildlife Area. The database will be used to evaluate GIS potential value in property management. There are projects pending for using GIS in wildlife research. The GIS is being used for developing graphics for use in a presentation at the Midwest Fish and Wildlife Conference. There are also plans for using GIS for studying deer movement in areas surrounding Brown County State Park and monitoring threatened and endangered species.

The Division of Water is examining possible GIS uses, in addition to survey plots and floodway mapping, in their floodway management program and water withdrawal regulatory program. The use of GIS in the water withdrawal program will allow staff to monitor spatial impacts of current and proposed permit holders on water supplies. In floodway management the Division is discussing a proposal to conduct a joint mapping study with the city of Indianapolis and it's IMAGES GIS.

Reservoirs Division has been working on two potential applications -- a property management database for Hardy Lake Reservoir in southern Indiana and a regional analysis of the Huntington, Salamonie, and Mississinewa Reservoirs in northeast Indiana. The Hardy Lake database will be used to aid property managers in planning activities to enhance the property for recreation and wildlife. The northern area is being studied to determine the impact of reservoir properties on forest fragmentation and habitat loss for woodland species.

The Division of Outdoor Recreation is in the process of determining requirements for transferring their recreational facilities database to GIS. The transfer would allow for greater use of spatial analysis in the planning process and allow for more rapid queries to the database to determine facility location.

Forestry is working to convert the continuous forest inventory into the GIS to allow regional foresters to utilize the data with other layers in the system or layers they will develop as a result of their field activities. The division is also working to use IDNRGIS in the preparation of Forest Plans for individual forest properties.

Activities and projects described above are all in the design or planning process and will be implemented in coming months. Successful completion of these projects will pave the way for new applications in other areas.

In the future the Department will place emphasis upon the areas of regulatory activities and environmental monitoring. The divisions with the regulatory functions, Reclamation, Oil and Gas, Water and Entomology have all expressed interest in utilizing this tool in their programs. The divisions who perform environmental review functions have also started to examine the use of GIS in making the review process more efficient and accurate.

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HOW A GIS CAN INCREASE A MUNICIPALITY'S CHANCES OF FUNDING INFRASTRUCTURE MANAGEMENT AND MAINTENANCE PROJECTS

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ABSTRACT

In municipalities across America, the news is out, and it's not good: our infrastructure is crumbling. Experts predict that spending to maintain and improve our streets, mass transit systems, water and wastewater treatment facilities, solid waste disposal plants, and airports must be increased annually from the current $95 billion to $156 billion by 1995. What most experts haven't outlined is how municipalities will go about determining problem areas, prioritizing improvements, and winning funding approval for infrastructure maintenance and improvement projects. This paper highlights our nation's infrastructure problems, proposes a 3-year plan for producing an infrastructure Geographic Information System (GIS), and suggests how municipalities can use a GIS to inventory, investigate, document, prioritize, and present information to increase their chances of winning funding for infrastructure maintenance and improvement projects.

INTRODUCTION: THE SCOPE OF THE INFRASTRUCTURE PROBLEM

In municipalities across America, the news is out, and it's not good: our infrastructure is crumbling. Bridges collapsing. Roads needing resurfacing. Contaminants polluting our water. Landfills closing. Every day another report about a vital component of our infrastructure demanding repair or replacement. In simplest terms, the nation's infrastructure rates a C-minus—barely able to meet our needs today and certainly not sufficient to meet our demands during future economic growth.

The National Council on Public Works Improvement, which gave our infrastructure this barely passing grade after studying America's public works for two years, delivered its final report to the President and Congress, *Fragile Foundations: A Report on America's Public Works*, in February 1988. Since then, other experts have tried to put a price tag on repairing and replacing our assets. Some recent reports call for consistent annual increases in public works spending from the current $95 billion to at least $156 billion by 1995 (1). The largest organization of construction firms, the Associated General Contractors of America, put the cost to repair and improve our nation's infrastructure at **$3.3 trillion**, more than enough to wipe away the federal debt (2). Facts and figures from the national council and other organizations paint a gloomy picture:

1. **Highways/Roads/Bridges:** C+. System expansion has not kept pace with growth in urban and suburban areas. Aging roads and bridges warrant major improvements. More than 60 percent of all paved highway miles need surface rehabilitation. To remain in service by the year 2000, 90 percent of the interstate highway system will need capital improvements. Structural deficiencies plague more than 40 percent of our nation's bridges that are over 20 feet long. Highway congestion has compounded; by the year 2000, vehicles on U.S. roads will be traveling 3 trillion miles annually, an increase of 33 percent (2). According to a 1989 *American City & County* survey of public leaders, almost 65 percent said streets and bridges were the infrastructure items most needing repair (3).

2. **Aviation: B-.** Airport congestion will affect three out of four passengers before the turn of the century. The number of seriously congested airports will increase a whopping 350 percent, from 16 in 1986 to 58 in the

year 2000. Even though more passengers crowd the nation's airports, no new commercial airports are under construction; the last commercial airport built at a new site was Dallas-Fort Worth in 1974 (2).

3. **Water Supply: B-**. Systems are deteriorating, supplies are limited, and source contamination is a constant problem. In some major cities, up to 30 percent of the water supply is lost each day because of leaky pipes (2).

4. **Wastewater: C**. Because of uncontrolled pollution, water quality has not improved, and water-quality violations have increased. America needs almost $84 billion to bring wastewater treatment facilities up to standards by the year 2005 (2).

5. **Solid Waste: C-**. More progress must be made in recycling and reducing waste. Finding adequate and safe facilities seems an unsolvable problem in the face of public opposition to landfills, which collect 95 percent of the 450,000 tons of garbage we produce daily. About half of these landfills will be at capacity and will close in less than three years (4).

Over the past 20 years, our investment in infrastructure has fallen off dramatically. In the late 1960s, net federal, state, and local government investment in public works was at 2.3 percent of the Gross National Product (GNP). By the first half of the 1980s, our investment had plunged to only 0.4 percent of GNP (5).

At the same time our infrastructure investment was on the decline, so was our productivity. Economist David A. Aschauer of the Federal Reserve Bank of Chicago blames our slowdown in infrastructure spending for the resulting productivity slack. In his 1987 study, Aschauer compared these parallel declines and cited international data to show that other countries enjoying productivity growth were countries spending the most on infrastructure. Japan, for example, spent 5.1 percent of gross domestic product on infrastructure and simultaneously watched productivity grow an average of 3.3 percent a year from 1973-75 (6).

Poor infrastructure has given rise to lawsuits against municipalities that have not maintained their fixed assets. The U.S. government recently won a suit against one southeastern state capital that neglected to keep up its water works system. After a water main break, the suit says, water escaped for more than two hours, resulting in tens of thousands of dollars in damage. Among the U.S. government's complaints: the city's intersectional maps showing valve locations were outdated, and the engineer's office and city water department maintained conflicting maps. By using inaccurate maps, the city water department took longer to curb the flow. The judgment against the city was affirmed upon appeal, and the city was ordered to pay damages. The message is clear: **Municipalities will be held accountable for maintaining the quality of their infrastructure and managing information about that infrastructure.**

A deteriorating infrastructure also does nothing to attract new business in a community and especially deters foreign investments. Even U.S. companies hesitate to locate in new areas with a problem-ridden infrastructure because they have no assurance that their products will move efficiently (4). According to the national council, "If we spend too little on public works or if we invest in inefficient projects, society loses more than the direct public cost. In the long run, our ability to compete in the international economy will be weakened, and our standard of living will suffer" (7, p. 10).

How did our infrastructure get into such trouble? Declining investments over the years are only part of the problem. **The other part is our failure to be long-range thinkers and long-range planners for the future of our infrastructure.** In short, we've been "shooting without a target." Operating without a clear vision for the future of our infrastructure, we have not been spending enough money in the right places. **As a result, infrastructure management has the potential to become the No. 1 political issue this decade in every state, region, county, city, and village in the U.S.**

Because our infrastructure is community infrastructure, its future affects all of us. We must start "re-aiming" by tackling the right infrastructure problems in each community. No public works project should be undertaken without someone asking "Why do this?" and "How will it help us in reaching our 5-year, 10-year, 20-year goals?"

A RENEWED COMMITMENT TO INFRASTRUCTURE

In an era of budget cuts and fiscal responsibility, we must learn to make the most of what we already have. That means **maintaining** our assets instead of constantly opting to build anew. Repairing a street, for example, is said to cost **three to four times more** than the cost of ongoing maintenance (7, p. 22). Historically, repair and construction projects have always gotten more visibility than simple maintenance. (Like the national council pointed out, there's no ribbon-cutting ceremony when a bridge is maintained.) Making maintenance more visible can be accomplished by providing easy-to-understand information about infrastructure conditions, performance, maintenance costs, and deferred maintenance (7, p. 21).

Along with our renewed commitment to infrastructure, we must make a brand-new commitment to managing infrastructure information. The national council put the challenge this way:

> "The Council strongly encourages all levels of government to upgrade the quality and quantity of basic public works management information in order to measure and improve system performance. At present, too many infrastructure investment decisions in America are made 'by the seat of the pants.' Small and medium-sized jurisdictions (and many large ones too) do not have complete inventories of existing facilities; most do not conduct regular surveys on the condition of public facilities or collect information on the quality, quantity, or cost of services. Only a handful of jurisdictions take advantage of established analytic techniques for computer mapping, life-cycle cost analysis, automated asset management, or precise tracking of growth trends" (7, p. 22).

By recognizing the severity of the problem, the National Council on Public Works Improvement realizes there can be no quick fix, no overnight switch in practice and attitudes. Instead, we must take deliberate, remedial steps. Among the council's recommendations is producing **improved performance information** to supplement what it calls traditional data: the extent, value, and condition of facilities. Performance information, on the other hand, shows whether new facilities are needed or if different facilities would be more effective. Performance information would allow the study of population served; actual use vs. available capacity; frequency of service interruptions such as delays, accidents, breakdowns; and frequency of health and safety incidents. By analyzing performance data, decision-makers would be able to provide service based on actual demand and to analyze cost-effective options before construction (7, p. 114).

The result? **More informed decisions by our public works leaders.** The council adds:

> "While the up-front costs and paperwork required to set up data collection, management, and reporting systems can appear formidable, the absence of this information means that public officials must make multi-million dollar investment decisions on an ad hoc basis. The costs of estimating required capacity incorrectly or selecting a project ill-suited to needs can be staggering, particularly in the face of the fiscal and economic pressures facing most state and local governments" (7, p. 22).
>
> "...despite the different backgrounds of public works decision-makers, the data and analytical techniques they need at all levels are remarkably similar. As much as 70 percent of the data could be shared.... Performance data should be automated to facilitate updating, analysis, presentation, and sharing" (7, p. 117).

Producing a Geographic Information System (GIS) is a deliberate, remedial first step we can take toward becoming long-range thinkers, planners, and infrastructure managers—and improving performance information.

The following three applications suggest the use of a GIS in the collection and analysis of performance data:

1. After analyzing characteristics of water mains that had at least one break recorded from 1987-1989, you determine that 55 percent were cast iron, between 8 and 12 inches in diameter, in silty loam soil, and were installed 20 years ago or more. You query the GIS again and determine what other pipes in the service area have the same characteristics; this allows you to project which pipes may break in the future. You then take action to monitor pipes with these characteristics more closely.

2. Construction is scheduled to start on a major downtown thoroughfare, which will be closed to traffic for the summer. By using the GIS to analyze alternative routes, you determine the two easiest detours for motorists to take through the city.

3. After querying the GIS and reviewing goals outlined in your capital improvement plan, you know that three roads totaling 8 miles need resurfacing within the next two years. By analyzing the condition reports of the associated sewer lines and water mains, you determine that a segment of one water main will need replacement in about three years. You put the need for this water main replacement on a top priority list of projects to be funded so that field crews won't be forced to tear up the newly resurfaced road one year later to replace the main line.

With GIS technology, we no longer have to make million-dollar decisions with public works dollars based on old data that often is neither organized, updated, nor in a format that allows analysis. **Producing a GIS allows us to organize traditional data so that we can begin collecting and analyzing performance data.**

FUNDING OUR INFRASTRUCTURE COMMITMENT

Along with our renewed commitment to maintaining and improving our infrastructure and our infrastructure management information must come a commitment to increase our level of infrastructure spending. Realistically, we can recommit to infrastructure only if the right funding mechanisms are available. Such a national priority demands more than a single-source solution; different types of funding—on national, state, local, and "user" levels—must be sought.

Typically, states have funded infrastructure improvements with general obligation bonds and special tax- or user fee-supported revenue bonds. In 1988, voters throughout the country approved 349 bond issues for public works projects for a total authorization of $14 billion, more than the total approved in 1986 and 1987 combined (1). Some speculate that voters are eager to approve ballot questions authorizing funds for projects that will ultimately improve their quality of life, especially in the wake of media coverage of collapsing bridges, closing landfills, toxic spills, and water pollution. This trend will likely make tax-exempt bonding an important part of overall infrastructure financing plans in the 1990s (8).

In Ohio in 1987, voters approved selling $1.2 billion in bonds until 1998 to finance infrastructure improvements and repairs through grants, loans, and credit enhancement. The state established 19 public works districts, each with a committee that reviews and rates funding applications for local governments within its jurisdiction. The Ohio Public Works Commission must approve all funding recommendations by the districts (9).

Other states have chosen different routes. Connecticut is financing debt for its transportation infrastructure program from a state motor fuels tax and transportation-related revenue, while Illinois is financing debt for its "Build Illinois" infrastructure program through the state sales tax (8).

Lease/rental-supported financing is another appealing option; many states do not consider this alternative as debt. Because the financing strategy is "pay as you go," assets can be funded over several years, and state revenue can be spent on other priority projects (10).

The National League of Cities (NLC) has outlined several unique infrastructure financing alternatives in its report, *Financing Infrastructure: Innovations at the Local Level.* Special financing, for example, allows the creation of special assessment districts within a particular political jurisdiction. Revenue is collected from property owners within the district to fund a project benefiting the landowners; however, a required number of landowners must approve this financing method (10). While this surcharge is over and above property taxes, the improvement financed with a special assessment district tends to increase property values (4).

Other methods of financing infrastructure projects exist, including sales and excise taxes, private sector donations, income tax increases, and user fees. While innovative financing mechanisms may help stretch infrastructure dollars, we must address the root of the problem and the long-term solution—better infrastructure management.

USING A GIS TO BETTER MANAGE INFRASTRUCTURE INFORMATION

Whatever we spend on infrastructure, we must be assured that we are spending it on the right projects. **A GIS can help public works decision-makers identify which projects are the right ones and when these projects need to be completed. In addition, a GIS can be a powerful tool for organizing public works data and winning funding approval for infrastructure programs.**

A stormwater project for Louisville, Kentucky, that ranked below a couple hundred other projects on a priority list for federal funding was moved to the top 10 once it became known that the city had a GIS in place. According to stormwater engineering consultant Steven C. McKinley, federal officials knew the project could be turned around quickly because at least 30 percent of the project—the data-gathering and mapping—was already complete because of the GIS (11).

In Ohio, a municipality can apply for infrastructure funding from the state Issue 2 bond program after it prepares a complete systems inventory and a 5-year capital improvement plan with supporting documentation. Jack Jensen, a consultant to the District 4 Public Works Integrating Committee in Montgomery County, Ohio, is responsible for reviewing state Issue 2 funding applications for the district to ensure they meet application requirements.

"One of the requirements under Issue 2 is that there be a complete inventory, and that inventory include a conditions assessment and a needs determination," Jensen said. "There is no question that any capital budget is enhanced by a good inventory system." While almost all funding requests are for valid projects, Jensen said, "a project many not get funded if it's not documented. If it doesn't meet the requirements, it will get turned down."

Jensen predicted that documentation will be looked at much more closely in the coming years and added that local governments must make a "good effort" to continually improve the quality of supporting information accompanying a funding application. If communities do not have their information in order, a public works project that might have been approved in the first funding year may be turned down in the fifth funding year. "The better the database, the better the (funding application) questions can be answered," he said. "A good database makes your whole program stronger...something needs to give you a first cut on what roads you will resurface this year" (12).

The city of Union, Ohio (pop. 6,000), recently received $834,000 in grants from the state Issue 2 bond program to fund five infrastructure improvement projects totaling $1.235 million. Supporting maps for the funding application were produced from the city's GIS.

"Using the system, it was easy to define the areas and show what we were trying to do," said City Manager John Applegate. One GIS map clearly demonstrated the need for a new water transmission line by showing how the city's old 150,000-gallon water tower was serving 68 percent of the city, while a new 500,000-gallon tower was serving only 32 percent. "To someone not familiar with the community, this (GIS map) is very valuable," Applegate said. "Our application looked good, read well, and provided the information required...and the mapping was a part of that" (3).

The bottom line? **If a municipality doesn't create a GIS, it is unlikely that it will receive a fair share of state or federal funding to maintain and improve its infrastructure.**

BARRIERS TO GIS IMPLEMENTATION/PERFORMANCE MONITORING

Although calling for automated systems containing the infrastructure management information needed to determine funding priorities, the National Council on Public Works Improvement recognizes that municipalities face obstacles to getting computerized performance measures—and sometimes even traditional data—in place:

1. Groups often disagree about data-collection standards.

2. New techniques are unfamiliar to existing staff.

3. Public agencies need staff with new skills that allow them to use the technology effectively (7, p. 118).

These so-called barriers need to be viewed instead as part of the equation in developing a GIS—necessary steps in the process. Groups need to sit down and work out standards for data collection. Staff must be trained to understand new techniques. And when necessary, a municipality needs to hire new staff with the desired skills. However, a fourth "barrier" suggested by the national council deserves further discussion:

> "Finally (and perhaps most significantly) [is] the time and expense required to establish and maintain the new data bases" (7, p. 118).

If we believe time and expense are the most significant barriers to GIS implementation (time is money, so what we're really talking about is money), we're accepting the notion that a GIS is a product—a commodity—instead of a professional service. **Because creating a GIS is a professional service geared toward the needs of an individual community, it cannot have a standard price tag.** The cost of a GIS depends on what the user needs and wants it for. Such applications cannot be calculated until some up-front planning is performed. Thus, a municipality cannot name time and expense as constraints to implementation without knowing what kind of GIS is best suited to its needs.

The conclusion that time and expense make a GIS prohibitive is based on old data from the late '70s and early '80s, when no "automated mapping" program could be performed for less than $10 million. Today, a municipality can implement a GIS as fast as it wants and as much as it wants—as long as the program has been planned and long-range goals have been set so that the GIS is created only once. We must remove the time and expense barrier if we are to become long-range thinkers, planners, and infrastructure managers.

A THREE-YEAR PLAN TO BUILDING AN INFRASTRUCTURE GIS

If utopia existed and funds were unlimited, we would create a GIS first before any master planning or capital improvement programming got under way. Realistically, however, a GIS must often be built throughout the master planning and capital budgeting process. Even if data for only one or two service areas, townships, or drainage basins can be input at a time, the GIS for these areas still can be used for more effective analysis applications.

As stated previously, a GIS is not a commodity; the GIS design plan that's right for one community may not work at all in another. However, it is worthwhile to consider some basic data needs for building a GIS for infrastructure applications. **The following 3-year plan for building an infrastructure GIS is intended to help municipalities start doing some long-range thinking about creating a GIS that is workable for their own community.**

The Year One GIS: Establishing the Foundation

During Year One, a municipality should concentrate on planning and establishing a solid foundation as the basis for the infrastructure GIS. Photogrammetry is the proven method for establishing a solid GIS foundation because it produces accurate, up-to-date information tied to a continuous coordinate system such as the state plane coordinate system. Once the geographic information is referenced to a continuous coordinate system, additional layers can easily be added in the future.

During Year One, a municipality could acquire aerial photography at 1″=800′ or 1″=1,000′ scale. Field crews could flag key aboveground water, sanitary, and storm utility structures (for example, manholes at intersections) before photography. To establish a basic framework, only edges of pavement, roads, bridges, commercial buildings, major drainage, and flagged utility structures would be photogrammetrically compiled. GIS maps at 1″=100′ or 1″=200′ scale, the most popular scales for preliminary engineering design and planning, could then be produced.

With the majority of the primary utility structures digitized accurately from aerial photography, additional aboveground utility structures could be added from existing source documents along with drainage areas, utility service areas, and political boundaries such as townships, city boundaries, and taxation districts.

As the network is built, the first attributes could be associated with physical features. Street names could be input, and a numbering system could be assigned to infrastructure elements. For example, unique ID numbers could be assigned to road segments so that a topological database structure is established. Once ID numbers are established for water, sanitary, and storm utilities, and once structure types are identified, additional attributes such as census/demographic data from any existing databases could be bulk-loaded into the GIS.

During Year One, the municipality should inventory field conditions for at least the major infrastructure components: primary roads/bridges and the water, sanitary, and storm utilities. Primary elements (for example, arterial roads, primary distribution lines) of each major infrastructure component should be ranked according to the condition observed from the field studies. (The conditions report would be the basis for a needs assessment, which would outline priority projects.)

At the end of Year One, a municipality would have an accurate framework for the GIS, which would contain edges of pavement; roads; bridges; commercial buildings; major drainage; water, sanitary, and storm utility structures (nodes and lines); and area boundaries (drainage areas, utility service areas, and political boundaries). Attributes such as street names, road segment ID numbers, utility structure ID numbers, and utility type codes for primary infrastructure elements also would be available in the GIS.

With the basic GIS framework established, the Year One GIS could be used to output special-purpose maps and reports needed for determining basic infrastructure priorities and for preparing funding applications. For example, the GIS could be used to produce site maps with all three utilities at various scales; show the location of a proposed water line in relation to existing structures; or produce a map highlighting the locations of all storm utility structures.

The cost? Consider the following: **The money spent simply locating utilities for a medium-sized city's various infrastructure projects over a single year would be sufficient to start a Year One GIS.**

The Year Two GIS: Adding Needed Layers

Year Two should be dedicated to adding additional boundary and utility data and related attributes, inputting attribute data from the conditions report, and digitizing property data in at least one geographic area within the municipality. (Once geographic locations are established, additional attributes should be added because they hold the key to implementing real-time applications such as computer modeling and capital improvement planning.

Property data is vital because infrastructure maintenance and repair records, billings, and complaint data—especially for utilities—to be added in the future are tied to properties.)

Additional lines and nodes for the water, sanitary, storm, and combined sewers, sanitary interceptors, and open channel systems could be added as well as associated attributes from either existing source documents or existing databases. As many as 30 or more attributes could be attached to lines; attributes such as rim and invert elevations, material, condition, and size could be attached to nodes—manholes, pump stations, treatment plants, storage tanks, regulators, and metering stations.

At the same time, boundaries and associated attributes for soils, land use, and zoning could be added to the Year Two GIS. Polygons could be set, and areas where polygons overlap (for example, zoning and land use; soils and land use, etc.) could be determined. Properties also could be input for one priority area within the municipality. For example, properties in an older area may need to be input first so that more detailed infrastructure analysis can be performed immediately in this area.

With additional attributes and layers input, the Year Two GIS could be used to output special-purpose maps and more detailed inventory and condition reports (which will indicate trends) and to determine more specific priorities for capital improvement planning. Summary information from more detailed analyses could be included with funding applications. The Year Two GIS could be used to highlight the locations of bridges with the worst condition rating; run a condition report on all primary sewer lines in the downtown area; or produce a map highlighting the locations of all water mains made of cast iron installed in silty loam soil.

The Year Three GIS: Adding Residential Buildings and Remaining Property Data

Priority areas for the remainder of the properties should be established during Year Three. Property data could be input per priority area from existing source documents after any necessary deed research is performed. Residential buildings, if required, and other information necessary to depict development could be compiled from aerial photography. Residential buildings, driveways, and parking lots, for example, would provide clues to the amount of impervious surfaces in a community. Such data is often essential in the development of a stormwater management utility, which could help generate additional revenue for repairing and improving the stormwater system.

Year Three takes the GIS yet another step further to increase a municipality's information management capabilities. The addition of the remaining property data provides new applications; for example, maintenance and repair data could be tied to addresses; future development issues could be addressed; and market analysis could be performed. The Year Three GIS could be used to produce a map highlighting all commercial buildings in one color and all residential buildings in another color for stormwater management applications; produce a zoning map containing property outlines for future development applications; or highlight the properties that would be affected if water mains with the worst condition rating would leak or break. These types of maps and others could be used as supporting documentation for infrastructure funding applications.

USING A GIS TO WIN INFRASTRUCTURE FUNDING

As shown above, a GIS under development can be used to produce various maps and perform basic and detailed analyses to document a municipality's need for a particular infrastructure project. For example, if one of a municipality's top-priority infrastructure projects this year is to replace a primary 10-inch water line with an 18-inch line, the GIS could be used to produce the following maps:

1. **Site Location Map.** The GIS can be used to output a vicinity map with the locations of all water lines and show the proposed location of the new line in the overall system.

2. **Maintenance Occurrence Map.** This map can show the number and location of breaks and leaks on this line over the past 40-50 years. A report can be generated that shows how much this maintenance has cost over the years.

3. **Impact Map.** The GIS can be used to show the impact on the water system and to residents if the 10-inch line fails. The precise distribution lines and properties affected by a potential collapse of the 10-inch line could be highlighted on a map.

4. **Future Development Map.** This map can show projected growth in the area and how the larger line is needed to meet the demands of this new growth.

Once these maps are produced, they can be included with documentation for funding and also used as the basis for reports summarizing inventory and maintenance data validating the need for a particular improvement. Not only can a GIS provide the supporting information necessary to win funding approval, but it also can be used for utility-specific master planning (for example, a stormwater management plan), computer modeling, future capital improvement planning, and daily operations and maintenance (for example, work order processing).

By using a GIS to develop a master plan, a municipality can get the "big picture" of how problems in one area of the city affect the system as a whole. With a GIS feeding a computer modeling program, more time would be available to analyze scenarios, evaluate impacts, and arrive at optimum solutions; without a GIS, engineers can only investigate a limited number of solutions. And by using the GIS for tracking ongoing operations and maintenance, detailed, current data will be available for the analyses necessary to prepare future capital improvement plans, the next step toward securing future infrastructure funding.

CONCLUSION

Our challenge in the infrastructure management crisis is to become long-range thinkers. However, because our political system is based primarily on 4-year terms, political figures often must spend more time campaigning for reelection than doing the long-range thinking and planning that benefit the community over the long run. Long-range thinking must be put in place to better manage infrastructure. We cannot afford to constantly rebuild only as soon as some vital piece of our infrastructure breaks, because downtime on an arterial road or primary distribution line has too much of an impact on the remainder of our infrastructure—and our lives.

A GIS that supports infrastructure should be a community GIS program and one that the whole community should help pay for. In the future, it is possible that GIS utilities, similar to stormwater management utilities, may be implemented so that community residents pay a portion of maintaining information about their community. GIS utilities may become a necessity because of the recurring problems that result from agencies and organizations in the same region maintaining conflicting infrastructure information.

Almost all funding programs require that a municipality have an inventory and an updated conditions report on its facilities. Maps and reports produced from a GIS can be used to make a case for winning infrastructure funding. Because a GIS provides the ability to organize and analyze our inventory and the condition of infrastructure facilities, we can begin to better collect and analyze performance data.

Producing a GIS and using it as a tool to win infrastructure funding is just one of the deliberate, remedial steps municipalities can take along the long road toward an infrastructure that is managed well and consistently to meet today's needs and efficiently and cost-effectively plan for the needs of tomorrow.

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BIOGRAPHY

Rex W. Cowden is a Partner with Woolpert. He is also the Director of the Geographic Information Services Division. Mr. Cowden has directed over 600 mapping projects that involve direct photogrammetric compilation, property and land use applications, utility data input and verification, planning applications, and engineering design applications. He is thoroughly familiar with Intergraph, Synercom, and a variety of other interactive graphics systems and software. In addition, he has extensive experience in designing and developing databases that meet clients' needs. Mr. Cowden's representative projects include The Franklin County Auditor's Office Appraisal GIS; Cincinnati Water Works; and the Cincinnati Area Geographic Information System (CAGIS).

Woolpert is a multidisciplinary firm engaged in the practice of photogrammetry and database mapping, civil engineering, planning, architecture, and landscape architecture. The firm, which employs more than 500 people, has been in business since 1911 and is based in Dayton, Ohio.

"IMAGIS" THE INDIANAPOLIS CONSORTIUM
ADDING WORK MANAGEMENT TO AM/FM

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August, 1990

ABSTRACT

The Indianapolis IMAGIS project (Indianapolis Mapping and Geographic Infrastructure System) is a consortium with eight (8) participants from the private and public sectors. The consortium was initially bound by a "Memorandum of Understanding" and ultimately by the "IMAGIS Service Agreement" between Indiana University and the eight participants. From its inception, the IMAGIS consortium was intended only to produce a county-wide comprehensive land-related digital database that would serve as the AM element of AM/FM (Automated Mapping/Facilities Management) projects for existing or future participants. Six (6) of the eight (8) participants have started FM applications. This paper describes the experiences of the Department of Public Works in incorporating third party Work Management software into its AM/FM system and discusses application costs and budgets for all city utilities.

INTRODUCTION

During 1986 and early 1987 the IMAGIS Executive and Technical Committees worked with the Consultant to develop specifications for database creation, hardware and software purchase and prepare the agreements that would bind the participants. Key features of the project include:

> Costs for creating and maintaining the land data base will be split 80/20 between public/private sectors
>
> The entire service area of 496 sq.mi. will be constructed from new aerial photography and positional accuracy will be ±2 ft.
>
> The IMAGIS database was completed over a four (4) year period (1986-1989) at an estimated total cost of $7 million or approximately $21 per land parcel. Database elements are shown in Figure 1.
>
> The hardware for storing and maintaining the digital landbase is housed at the local campus of Indiana University/Purdue University (IUPUI). IUPUI Computer Center will also provide operating services such as data backup and software loading.

Figure 2 schematically shows the organization and the relationships among the participants. It is important to note that the Department of Metropolitan Development (DMD) has been designated as the "keeper of the map" and bears the responsibility for updating most map elements. DMD will add parcel, zoning, building footprint information and land use information as it is captured through the zoning and construction permitting processes. Actual building footprints, elevation contours, impervious surfaces, etc. will be captured through periodic photographic updates.

ADDING WORK MANAGEMENT (AM/FM/WM) IN THE DEPARTMENT OF PUBLIC WORKS

The vast majority of the activity in an organization that manages any type of community-wide facility occurs in areas other than planning and engineering. The majority of activity consists of monitoring the level of service provided, acting on customer requests, physically maintaining the facility, issuing and recording work orders, maintaining inventories and rolling stock, managing a labor force and cost accounting. In general these activities are called Work Management (WM).

The Department of Public Works manages several County-wide programs including sanitary sewers, drainage and flood control facilities, solid waste collection and disposal and air pollution control. The Department's strategy is to implement an automated Work Management (AM/FM/WM) system for each of its major programs over a several year period as budgets allow and sewer programs were scheduled first. There are a few sewer maintenance Work Management packages on the market, but none were found that produced maps or communicated with mapping packages. An RFP was issued to firms that offered a sewer maintenance Work Management package that:

* Ran on, or had the ability to be ported to, the VAX VMS environment

* Demonstrated the ability to transfer files to and from the Synercom system and produce maps while in the sewer maintenance package

* Managed all phases of a sewer maintenance program including physical inventory, cleaning, construction, inspection, complaints, fleet management, labor, and materials.

The RFP also required that the firm provide a turn key package including all data conversion. Four firms responded to the RFP and Hansen Software was selected as the vendor best able to fulfill our requirements. Figure 3 is a schematic of the basic features of the Hansen package.

The IMAGIS Consortium

In defining the interface between the Work Management (WM) package and the AM/FM package, it was recognized that both packages had data base management abilities. Two (2) broad questions that had to be answered were, "How do we keep from duplicating data in the two data bases?" and "Which data base manager should be relied upon for day-to-day activities?" It was concluded that while most sewer maintenance activities have geographic significance, they are not geographic in nature and do not require the powers of a mapping system data manager. Any activity can be located on the map merely by knowing the address of the activity or sewer segment number, both of which exist as attributes in separate data layers in the AM/FM data base. Figure 4 shows that the interface between the two databases occurs through either address or sewer segment number.

Producing a map of sewer maintenance activities can be accomplished by transferring address or sewer segment files that have been produced by standard query of the WM database. The Hansen package produces ten (10) standard mapping routines from the various modules in the WM package. For example, the construction work order routine will produce a file of segments that have had a certain type of repair or perhaps have barricades in place. The complaint routine will produce files by either address or segment number that can be mapped to help diagnose problems.

FM/WM BUDGET FOR SEWER MAINTENANCE

The IMAGIS strategy calls for the consortium to own only the AM hardware and software while each participant must obtain separate hardware to perform its FM/WM applications. The Department spent the following to implement the entire sewer FM/WM program including hardware and mapping software capable of supporting other Department programs:

Hardware Purchase	$ 200.000
Software Purchase (Synercom and Hansen)	300,000
Data Collection and manual mapping	1,500,000
Convert manual maps to digital layer	75,000
Convert sewer records to digital database	300,000
Total	2,275,000

This program costs approximately $11 per connected customer and approximately $0.18 per linear foot of sanitary sewer. Figure 5 compares the relative cost of implementing and maintaining the FM/WM system to other activities that commonly occur in a sewer program such as smoking and rehabilitation. In terms of relative cost, the 18 cent ($.18) per foot investment in a management system is nearly one tenth of the cost of manually inspecting one foot of sewer.

The hardware component of the FM/WM system costs $2.90 per connected customer and includes a CPU and communications network capable of supporting most of the Department's future needs. The Department's philosophy is that every one who either uses or builds the data base should have fairly easy access to it. Therefore, the network reaches the Engineering, Customer Service, Sewer Maintenance and Leakbusters Divisions. The network installed is shown in Figure 6.

The network connects four (4) remote sites and will eventually expand to six (6) sites. One of the features of the Work Management package is its ability to download to, and upload data from, laptop computers used by field people. There was initial reluctance to use laptops for data entry in the field, however after one or two day's use, the laptops became very popular. At the start of the day's work a supervisor down loads the database for the sewer segments that each crew will be working on. Inspection data is then entered directly into the laptop. Downloading occurs at the end of the day and avoids the transfer of paper record for each segment. So far, only TV inspection personnel are using laptops, but future software updates will allow other types of field data to be entered through laptops.

USING IMAGIS FOR SOLID WASTE COLLECTION

Solid waste in Marion County had historically been collected by the Department's crews in the inner city area and by 25 companies in disorganized fashion throughout the remainder of the county. In the suburban areas, individual homeowners contracted for collection services and as a result a subdivision could be receiving solid waste pickup five days per week by five or more haulers. In 1990 the Department expanded its control of collection of 220,000 homes throughout the county. Each hauling company was awarded a geographic area with approximately the same number of homes it served prior to the expansion. A software package was needed to:

Create the areas to assign to hauling companies.

Count the homes in each area

Send bills to each address in each area

Track billing and payment history for each address

Track service requests or complaints for each address

Pay each hauler for the number of homes in its area.

Because the IMAGIS database was being completed and debugged during the time the expansion was being prepared, the engineers were often forced to perform the task both with manual and computerized methods. Figure 7 is a table of the costs being experienced doing this work both ways. Setup costs were higher for the computer based system of establishing hauler areas however annual costs were lower. Figure 8 shows that the payback for this investment occurs after the third year of operation.

COSTS FOR CITY WIDE INFRASTRUCTURE MANAGEMENT

An informal survey of AM/FM users shows that the cost to create an FM application that incorporates data for each customer falls in the range of $5 to $15 per parcel. Data conversion is the greatest cost for these applications and the existence of an automated data base can keep the application cost at the low end of the range. The IMAGIS participants were asked for the costs they had either spent or were budgeting for creating their FM or WM applications. Those costs were converted to a per customer or per parcel basis and are shown in Figure 9. This table shows that the costs for implementing these applications and creating a base map can easily be in the range of $100 per parcel. This cost is much higher than most people anticipate, however when compared to a revenue stream of $3000 to $4000 that a parcel can generate each year in taxes and utility fees, a $100 investment that can provide better service over several years seems wise.

DATA BASE ELEMENTS

BOUNDARIES/AREAS
- Census tracts
- City boundaries
- City planning areas
- City-standard grid area boundaries
- County boundaries
- Drainage basins
- Flood zones
- Plot/plat/lot boundaries
- Public lands (city, county, etc.)
- Special assessment areas
- Subdivision boundaries
- Tax areas
- Township boundaries
- Utility franchise area boundaries
- Utility index maps

CONTROL
- Geodetic control
- Survey monuments

LABELS/ATTRIBUTES
- Block (by number)
- Land ownership
- Parcel number
- Parcel/house addresses
- Parking lots
- Parks
- Plot/plat/lot number
- Street names
- Subdivisions/additions
- Topographic info.(spot elev., benchmarks)
- Vacant lots - improved, unimproved

LAND USE (Zoning, planning)
- Land use, existing
- Land use, planned
- Land use, zoning

NATURAL FEATURES
- River channels
- Rivers, creeks, streams
- Topographic information (contours)

PHOTO-IDENTIFIABLE FACILITIES
- Culverts
- Fire hydrants
- Flood controls, levees
- Manholes
- Poles

RIGHT OF WAY/EASEMENTS
- Easements
- Public R.O.W.

STRUCTURES
- All commercial buildings
- All industrial buildings
- All residential buildings
- Bridges
- Hospital/health facilities
- Public buildings
- Sewer plants and lift stations
- Shopping centers

TRANSPORTATION
- Railroad crossings
- Railroad tracks and land
- Sidewalks and acknowledged pathways
- Special boulevards and parkways
- Street delineation (curb & edge of pavement)

Figure 1

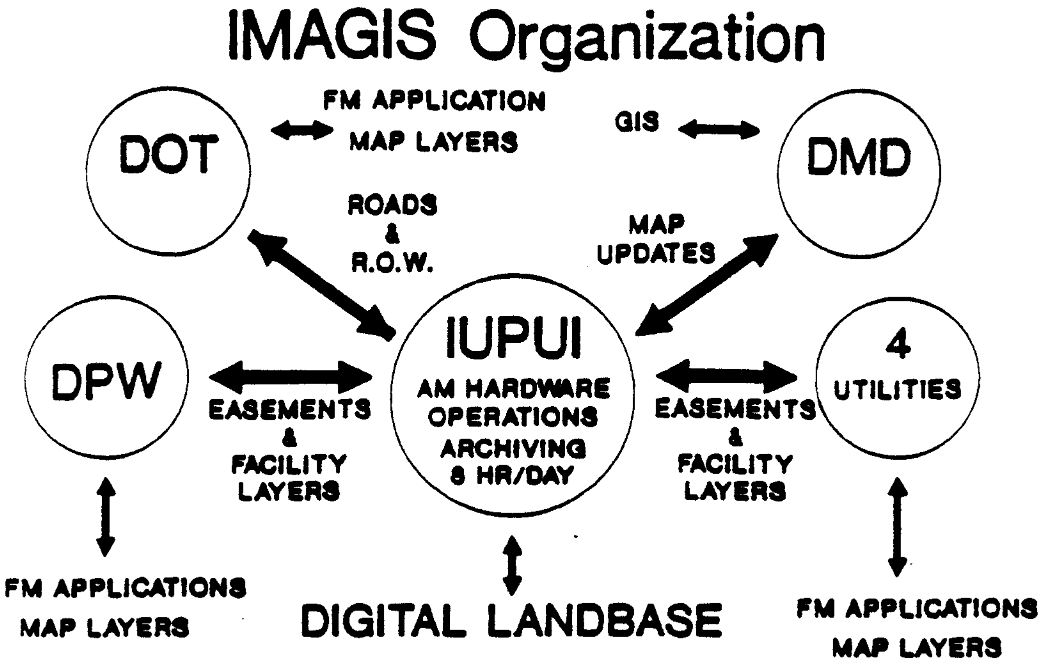

Figure 2

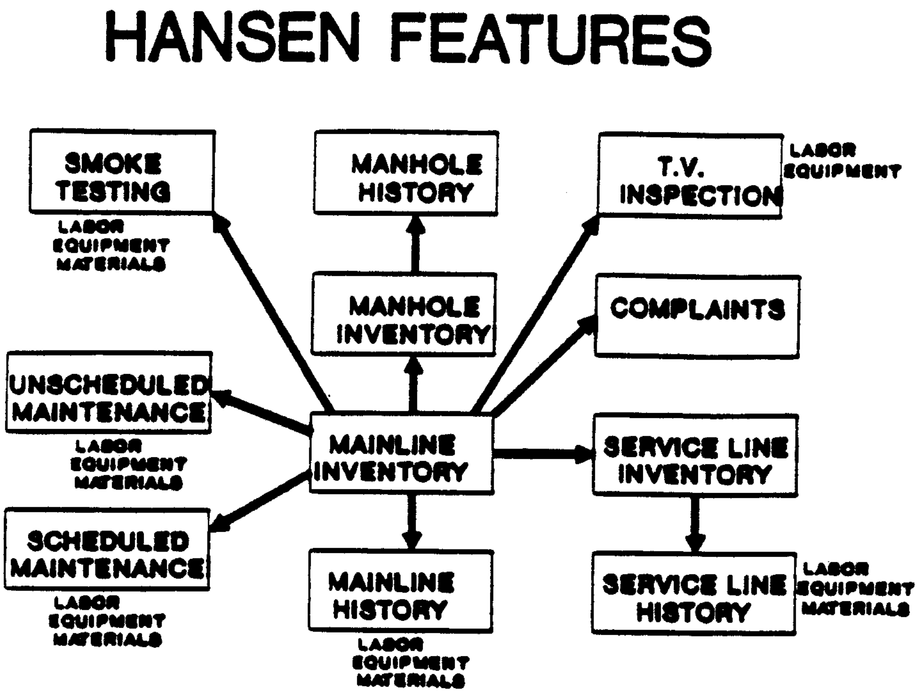

Figure 3

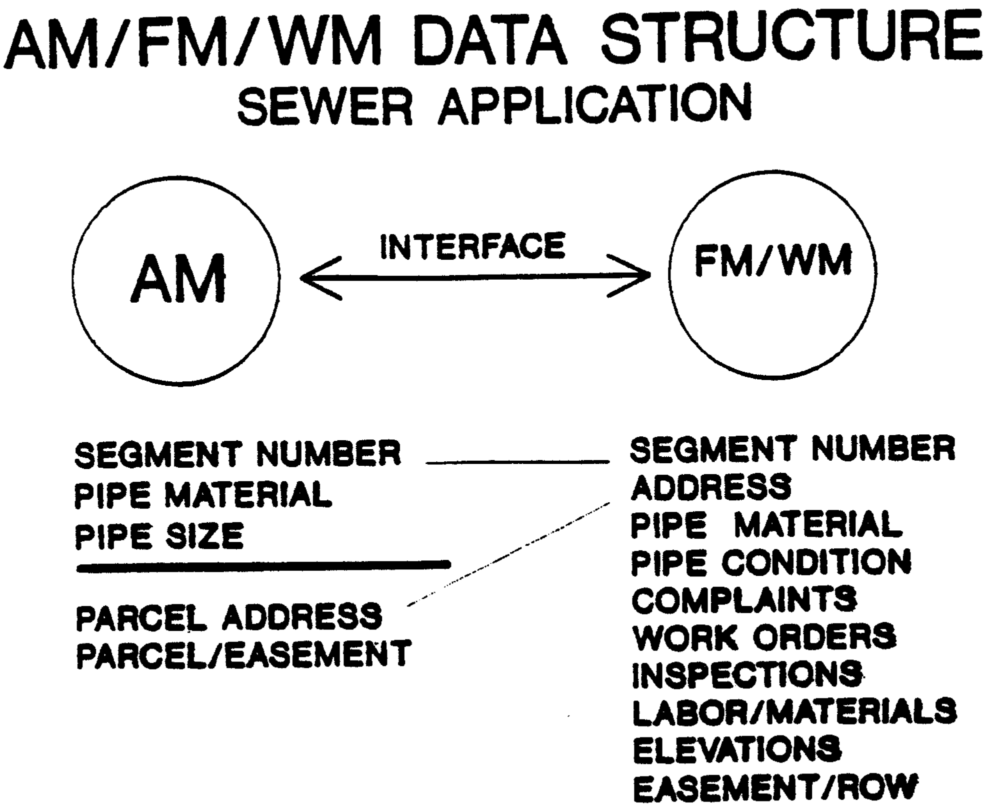

Figure 4

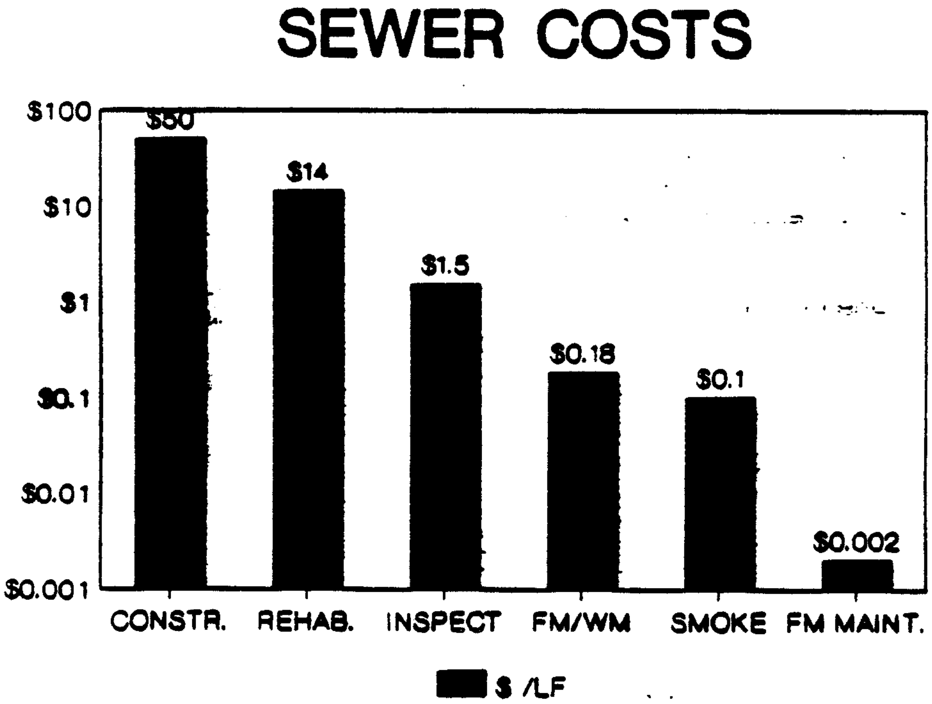

Figure 5

NETWORK CONFIGURATION

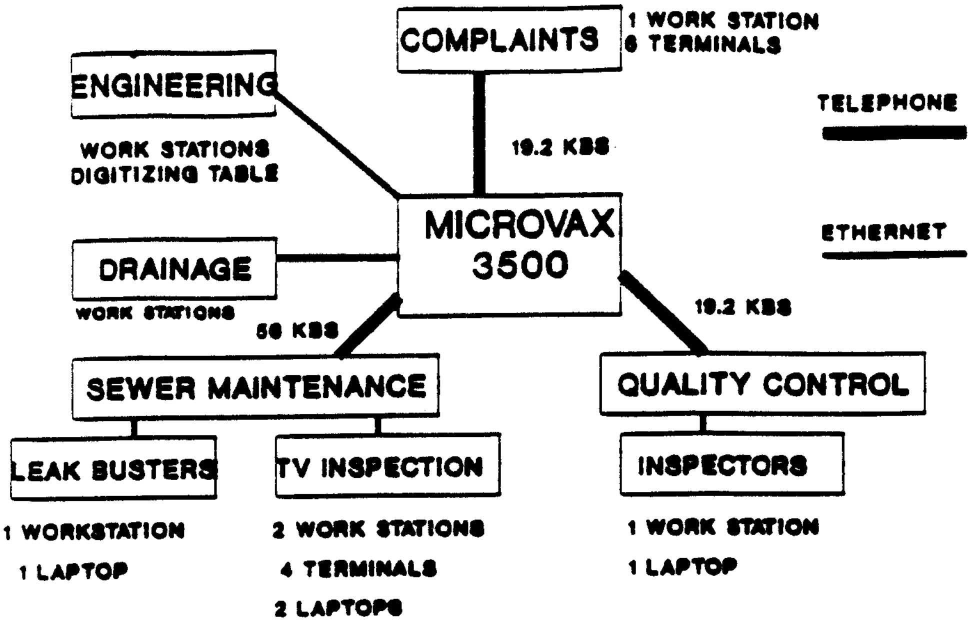

Figure 6

SOLID WASTE APPLICATION

PROJECT COSTS ($1000)

	IMAGIS		MANUAL	
	FIRST COST	ANNUAL	FIRST COST	ANNUAL
DEFINE AREAS	3	1	30	5
VERIFY ADDRESS	230	1	230	20
BILLING SOFTWARE	973		973.	
HARDWARE & SOFTWARE	323	10		
SERVICE REPS.		150		325
TOTAL	1,529	162	1,233	350

Figure 7

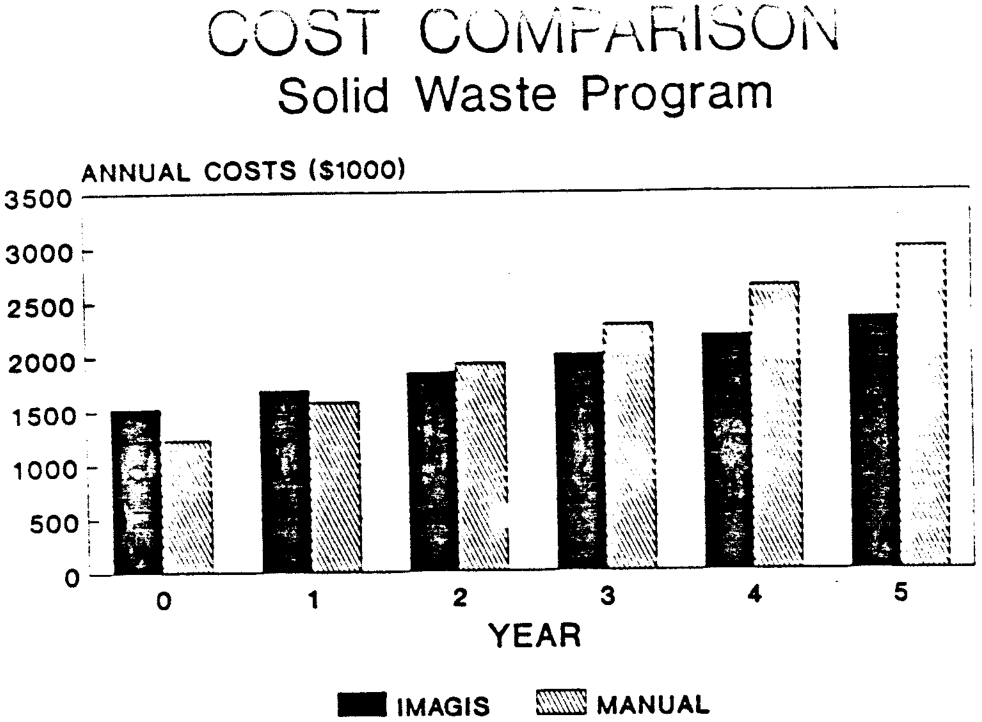

Figure 8

IMAGIS COST FOR INFRASTRUCTURE
$ / CUSTOMER - PARCEL

AM (BASE MAP)	30
SEWER FM/WM	12
WATER FM/WM	12
GAS FM/WM	16
STREETS FM/WM	8
SOLID WASTE	7
TELEPHONE	4
ELECTRIC	6
STORM WATER UTILITY	10
TOTAL	105

Figure 9

GLOBAL POSITIONING SYSTEM: CONTROL TODAY

Jeff Meyerrose
MSE Corporation

Technology in the survey arena has developed rapidly in recent years. This development has been seen in conventional surveying with the influx of total stations and data collection systems, but more drastically impacting a particular phase of surveying is the impact that Global Positioning Systems have had on control surveys.

This paper will address the advantages of utilizing GPS on major GIS projects as well as photo control jobs and projects with smaller scopes of service. Advantages to be discussed will include economical considerations, logistical considerations and timing considerations.

All of these advantages are from the perspective of a consultant with hands on experience and with diverse involvement on projects from photo control to GIS base mapping and primary control.

The Egyptians who laid out the magnificent pyramids with a high degree of precision are considered the first professional surveyors. These masters of pyramid construction did the control work using knotted ropes and a relative direction instrument known as a "Groma". This early survey work, as it turned out, resulted in the accurate layout of some of the largest, most labor intensive construction contracts in history.

Early sailors were astronomic surveyors of sorts as they utilized the celestial bodies to assist them in navigation. Instruments of that trade included the sextant and compass. Sailors and explorers skirted the profession of surveying and cartography when they charted lands previously unknown. Some of these early maps, although constructed archaically, were relatively representative of land masses and considering the era, very well done.

Early Americans used Rittenhouse compasses, and 66' chains in laying out the sectionalized rectangular system that we are familiar with today. With the aid of solar observations, it has been found that this early work, when completed by competent and respected individuals of the day, was quite accurate. Even as we see today, there are varying degrees of diligence in all professions. Surveying is no exception. With proper care and supervision, the tools of the trade allowed for the end result to be an acceptable product to the end user.

The United States went through a major control growth period during the 1920's and 1930's. At this time, the United States Coast and Geodetic Survey, (National Geodetic Survey) and United States Geological Survey began to perform horizontal traverse. This period saw 1st order triangulation and trilateration stations densified across the country. A great deal of this work was done at night to avoid the daytime disturbances of heat waves. Lights were used as points for foresights and back sights. Because of topographic relief and/or obstructions it was often necessary to construct towers to lengthen the line of sight available. As had been the case with these and similar operations, weather was a key factor in determining schedules. It was either very difficult, extremely uncomfortable or impossible for survey work to be done in inclimate weather. The difficulty or impossibility arose from either the physical inability to see from station to station or the extreme demands made on personnel. Nonetheless, after several years,the United States ended up with a good control system. It is worthy to note that all of these epoches in history spanned many generations. The surveying arena has been traditionally one that has been slow to change; until the last twenty five years.

Over the last quarter century, our technology has brought us a higher order of accuracy instruments at lower costs, making it affordable for more groups to perform precise survey work. Instruments like the Wild T-2 are direct reading instruments to one second of arc. The quality and affordability of the optics was the driving force in directional instrument availability. But direction is only half of the formula for efficient traverse derived survey control.

The answer to distance definition in survey was the Electronic Distance Meter or EDM. Over the last twenty five years, EDM has gone from a large, heavy and time consuming piece of equipment to a light, adaptable and quick (oftentimes self contained in the theodolite) system. The EDM's progression is similar to that of the computer, which evolved from a mainframe the size of a room to the powerful hand held calculator. However this duo is packaged, whether as theodolite with top-mounted EDM or as a total station, it will always be necessary for all types of survey applications.

Also helping to streamline the traverse process is the use of data collection directly from the theodolite and EDM. Many different systems are available and can be customized to an individuals needs. The advantages of internal data storage include a reduction or total elimination of field note errors. This reduction is due to transposition in field notes and the increased efficiency in note keeping. As we make the natural progression, it becomes apparent that data from the field must be processed. Data collection systems can be readily downloaded onto personal computers and batch processed to create plots or coordinate geometry files.

The primary limiting factor in the use of theodolite and EDM is the necessity to maintain a clear, uninterrupted line of site from point to point. In remote areas with trees or in developed areas with vehicular or pedestrian traffic, the line of sight requirement is the Achilles Heel to survey work. Production rates for horizontal traversing with conventional survey equipment is from one to three miles per hour in average terrain, depending on the accuracies to be achieved. The accuracies achievable with conventional survey equipment is from 1" in 20,000 parts to 1" in 100,000 parts or from 0.1 to 0.03 feet in one-half mile.

But there is a new development that has (or soon will) taken the surveying community by storm. This development is GPS - Global Positioning System. The system is made up of three integral operating units: GPS satellites, GPS control system and GPS receivers.

Satellites are deployed by manned as well as unmanned launch missions. The space shuttle program was to be used extensively for satellite deployment until the Challenger disaster. Notwithstanding that, there are currently (15) working satellites. These satellites have been put into orbit by Delta Rockets and are under the jurisdiction of the United States Department of Defense. Information transmitted from the satellites is provided and monitored by ground control stations.

These control stations are located around the world. The Master Control Station in Colorado Springs, Colorado, provides and receives information from other stations in Diego Garcia, the Ascension Islands, Kwajalein and Hawaii. The five ground tracking control stations record readings from the satellites to calculate orbits and time offsets. The Master Control Station in Colorado Springs uploads ephemeris data, almanac data, and health and timing information.

The user's segment includes surveyors and geodeticists who utilize the system for location, and groups who develop and monitor various modes of travel such as aircraft and shipping. As was indicated earlier, the satellites are primarily intended for military uses and are maintained by the Department of Defense. For security reasons, scrambling of some signals does take place. However, ephemeries data is available for post processing so data collected during what is known as "Selective availability" can still be used.

So what are the advantages and disadvantages of using GPS from the traditional surveying perspective? The three areas I would like to touch on are:

Economical Considerations
Logistical Considerations
Timing Consideration

Although all of these considerations are related, each one will be addressed on an individual basis to increase clarity.

The first economically related issue is the cost associated with the hardware necessary for a GPS system. Receivers, as utilized for surveying applications, range in price from $15,000 to $80,000 each, depending on the manufacturer and specifications of the unit. Since a minimum configuration for survey applications is two units, and three or more are desirable, it becomes apparent that this technology is not for every firm. There are alternatives to purchasing units, such as daily rental and long term leasing, but each of these alternatives should be weighed. Additional costs associated with the receivers are items such as travel cases, extra batteries, a computer powerful enough to process the data, a printer, and software for network adjustment and report generation. With everything included, it is not difficult to spend $120,000 to $150,000 on equipment alone. Clearly all of this cost must be offset somehow.

Locations of unknown points can be achieved plus and minus a few centimeters, depending on baseline length and control network configuration. No matter how many receivers are used, the total number of new points achieved per session is the number of receivers minus one, assuming one unit is held at a known location for control. Therefore, in a four unit configuration three new points are established in each session. Assuming these points are five miles apart, fifteen miles of traverse could be completed in one hour or less. This ability to establish control over a large area in a short period of time, with a high degree of accuracy, is the major advantage of GPS. Again, point intervisibility is not a requirement. Range limitations exist for each unit and are available from the manufacturer. Atmospheric conditions play a considerable role and may alter the length of baseline obtainable.

Fees for GPS points vary tremendously depending on the specifications required and additional involvement on the part of the survey consultant. Anything that the client can do in assisting the consultant will help lower the per point cost. Consultants are able to provide criteria for monument construction and placement (relative to GPS observations) and reference requirements that can aid in lowering the per point cost. Generally speaking, when utilizing static differential GPS surveying, prices per point range from $200 to $800.

Logistical Considerations on Global Positioning Systems are numerous. Pre-mission planning is absolutely vital. This phase can make or break the entire project. Reconnaissance of points to be occupied, safety of individuals, communication between members of the party and alternative plans in the event of unscheduled delays all need to be addressed. GPS is a labor intensive technology. With a four unit configuration, at least four people and four modes of transportation will be required to operate efficiently. For the most part, logistics that apply to conventional geodetic surveying also apply to GPS, with one major variance... line of sight is not required. MSE has been able to provide control on a wide variety of projects using GPS. Projects vary in scope from major GIS projects, such as Southern California Gas, where GPS controlled the COGO input of several tens of thousands of parcels, to fairly tight constraints to third order photo control that requires reference to state plane coordinates. Another major utilization of GPS is initial control for boundary work. Associated with this application is a logistical concern that the limitations of the equipment must be considered. Current GPS receivers will measure in differential mode to plus and minus/centimeters plus parts per million, depending on the baseline length. Because of the 1 centimeter deviation, baselines of one-quarter mile length have a maximum accuracy of 1:40,000. During the adjustment process, short baselines, processed simultaneously with long baselines, will provide biased results. Knowledge as to cause and effect in these instances is invaluable to the consultant. Therefore, at MSE, the use of GPS has been restrained to providing control at intervals not closer than one-half mile and then densified by conventional survey techniques.

Another logistical concern that is erased with the use of GPS is that of inclimate weather. The receivers themselves will function in weather extremes with the same consistent results. The collection of data will, for the most part, not be affected by driving rain, snow, wind, heat, cold, night or bright sun.

Two areas of concern from a weather standpoint affecting GPS are atmospheric differentials (primarily over long baselines) and solar activity. Atmospheric differentials will cause signals from satellites to travel at different rates to receivers that are a considerable distance apart. For receivers within relatively close proximity, this is not a consideration. Solar activity is cyclical on ten year highs and lows. The effect of both of these phenomena can be reduced or eliminated by utilizing dual frequency receivers. However, the hardware costs are significantly escalated.

Timing considerations deal primarily with pre-sission planning. Although it is not a single process, this is by far the most crucial phase of GPS surveying. Time must be made available for sufficient data collection, travel between observation stations and post processing. One advantage of GPS from the timing standpoint is that GPS can be used at night. As was mentioned earlier, all considerations are related, and nighttime surveying carries with it varied logistical concerns.

When considering method of traverse or point location, the use of GPS or conventional methodology or a combination of both should be estimated. The use of GPS becomes tremendously advantageous over large expanses or in areas of very little pre-existing control.

Although the uses of GPS during this presentation have centered around its use for control, there are many other applications. GPS has been used for years in navigation and will continue to be developed for "To-From" navigation. The use of GPS on construction equipment farm machinery, emergency and/or service vehicles is all within the near future. Additionally, resource managers currently use GPS for inventory purposes.

It is clear that this technology will be here for a long time and the uses and applications are for us to determine. But for today, GPS has certainly found an application in the control arena.

GIS AND THE INDIANA DEPARTMENT OF TRANSPORTATION: MAPPING THE ROAD TO A BETTER INFRASTRUCTURE MANAGEMENT PROGRAM

INTRODUCTION.

The primary mission of the Indiana Department of Transportation (INDOT) has been determined as "providing leadership in establishing safe, reliable statewide transportation systems that ensure the efficient movement of people and goods and promotes economic vitality within Indiana". With the help of Geographic Information System (GIS) technology, INDOT expects to carry out this mission with increased efficiency and expanded capability, thereby bringing a higher level of service to the citizens of Indiana. INDOT has initiated its GIS program with the acquisition of state of the art hardware and software. The next step, then, is to define how the hardware/software platform can best be used to facilitate the mission of INDOT.

That definition involves answering a series of basic questions that have to do with how INDOT perceives the current technology, what kind of data is available to populate our GIS, how to get started, what groups within our organization will benefit from GIS technology, what payoff and benefits can be expected, what has been accomplished to date, and finally what future technology might have in store for us. The answers to these important questions will provide the direction for the creation and evolution of INDOT's Geographic Information System.

HOW DOES INDOT PERCEIVE GIS TECHNOLOGY?

A Geographic Information System, in its broader context, includes four fundamental components. It begins with raw data that is collected and organized in either paper or digital form. The data is processed with the software and hardware tools that are guided by human interaction. The resulting information is then distributed to users.
Preferably, and as is often the case, the human interaction that shapes the raw data into information is also the end user.

RAW DATA ELEMENTS:

We sometimes overlook the fact that raw data is merely the material used to build information. While the collection, organization, and output of raw data can, in and of itself, be meaningful, its higher importance is its potential of being converted into powerful decision supporting information. That is as true for graphical data, such as maps of electrical circuits, land parcels, or transportation networks, as it is for tabular information like voltage, phase, property value, acreage, or average daily traffic.

In Department of Transportation terms, the raw data building blocks are graphic components from USGS DLG-3, electronic field survey, construction drawings, aerial photography, and legal descriptions of land parcels and political boundaries. The tabular data is made up of attributes such as average daily traffic, pavement condition, right-of-way width, and accident location which have been collected and computerized over a number of years. The computer tools which will process this data are based on McDonnell Douglas graphic software, GDS, powered by Digital Equipment's Vax series and tied to IBM's relational database, IDMS.

SOFTWARE PLATFORM:

GDS is a graphics system with object intelligence, that is, each graphic object has the potential of knowing what it is, as opposed to merely what it is composed of. As an example, an object, such as a segment of roadway, could contain the intelligence to know that it is US 31 in Johnson County and that it begins 5.64 miles north of the county line and ends 3.56 miles further north. This kind of object intelligence is much more informative than traditional element descriptions which might define the road segment as a collection of linestrings and arc elements with particular graphic qualities. What is unique about object intelligence is that this information can be retrieved from the graphic element itself without ever opening a database. When topological structuring is added to object intelligence, as it will be at INDOT, the resulting graphics are extremely powerful.

This graphic package will be linked through a hardware/software gateway to continuously updated road inventory, physical features, roadway management, and traffic accident location data which is relationally organized within IDMS. This attribute data is invaluable for providing both snapshot assessment and historic trends.

In addition to GDS and IDMS, INDOT users will be taking advantage of the capabilities of COGO/ROADS (COordinate GeOmetry/ROadway Analysis and Design System). The COGO program will be used to solve geometric problems. It allows the user to input the information in a manner similar to the way the surveyor would lay-out alignments or traverses. The program allows the user to solve for unknown variables and adjust for errors in traverses. ROADS automates the traditional procedures involved in roadway design, cross-section production, and earthwork quantity calculation. This program allows the lay-out of roadway features such as widening, superelevation, ditch grades, and measurement of various existing earth materials in a more complete manner than any other roadway design program investigated by INDOT.

MOSS (MOdelling of SurfaceS) produces a three-dimensional model of the topographical data within its model files. Proposed roadway alignments and required cross-section data may be obtained by graphically laying out the desired alignment anywhere on the model. This enables the designer to adjust the roadway in any manner needed to produce the most efficient layout, and still obtain an accurate representation of the ground where the work is performed. It also allows the designer to develop complex features, such as interchanges, in a far more accurate way than can be done by traditional cross-sectioning methods. Proposed roadways are defined by the engineer in a similar manner to that used by ROADS.

HARDWARE PLATFORM:

The DEC side of INDOT is powered by a MicroVAX 3900 and 3600. These machines are connected to distributed VAXstation 3100s and VT 340 terminals. The network is Thinwire Ethernet. Data storage is on five disk devices providing nearly 4 GigaBytes capacity. Peripheral devices include text, dot matrix and Laser printers as well as pen and electrostatic plotters.

The IDMS database is powered by an IBM 4381 mainframe connected to nearly 500 users with a large disk farm for storage.

WHO ARE THE USERS WITHIN INDOT?

Engineering Services. Within the engineering services department of INDOT, both the cartography and contract sections will be taking advantage of GIS capabilities. The cartographers will be developing "specialty" maps for use in presentations to local authorities, legislators, and private individuals who might be concerned with a particular region of roads. Generally these maps will be specific roadway data, such as road deficiencies or traffic counts, overlaid onto the base map. Such maps will also be useful to district or central office personnel to help select routes for future projects.

The contract section handles the final FHWA approval of federally funded projects and the contract letting process for all projects. As part of this process, Contracts personnel review the final plans to ensure that all required special provisions are included in the contract documents. The review of the plans will be made more efficient by using a graphics station. The workstation will only require the capabilities of viewing the plans and adding some notes for the designers on the Contract Section's own unique layer. Viewing the plans on the workstation will also ensure that the most current version of the plans is being inspected.

Program Development. The Preliminary Engineering Studies section of this division prepares engineering reports which analyze proposed routes for future projects. With the help of interactive graphics and design software, a greater number of alternate routes may be examined to a greater degree of accuracy. The production of the Engineering Reports will also benefit from access to the Road Inventory Database which can provide information commonly used in these reports.

Design. "Field book" data, consisting of both the electronic data and notes, will be assembled in the Survey Section so that completed topography, ready for use as plan sheets or details will be presented to the Design squads in electronic form.

Plan Development has been the first area to obtain workstations to take advantage of the CADD capabilities of the software. The preparation of road and bridge plans will be the primary function of the system within the Plan Development group. As much of the plan preparation process as possible will be performed on the computer.

Topography will be supplied in electronic form to the designers. The plans will be laid out by the designer on the workstation instead of on paper. The draftsman will layout final details and monitor the plotting of the plan sheets by the design unit's plotter. The designers will also benefit from the accessibility, through their workstations, of various engineering programs.

The production supervisors in the design units will require graphics stations for the review of plans.

Traffic Engineering should realize a significant increase in productivity. Particular details required for signing, signalization, illumination, or channelization plans will be electronically copied and revised as needed for use in various projects. Any traffic details which are prepared for inclusion in road plans can be transmitted in electronic form to the designer responsible for the road project.

Design Consultant Services personnel will require CADD workstations for their duties of checking plans when all consultants can consistently submit check plans electronically.

The Standards Section of Design will maintain road and bridge standards in electronic form. Designers will be able to copy and include in their plans the approved versions of the standards, which will be accessible from any workstation. The designer's copies of standards may also be altered as necessary to produce "special details".

The Hydraulics/Hydrology Section will be able to use a CADD workstation for the calculation of drainage areas. When this section checks pipe sizes or bridge waterways on the highway plans, the plans can be transmitted electronically to the Hydraulics Section and called up for review on the workstation. This section will also have access to various runoff and hydraulics programs on the workstations, as will the designers.

The Utilities and Railroads Section functions primarily as a liaison between the plan development sections and the appropriate railroad or utility owners in the area of a particular project. This section will review the plans on station for possible conflicts between the road constriction and the utility lines.

LAND ACQUISITION. The Engineering Section of Land Acquisition will be that division's major user of the graphics system. Currently, the copies of the approved R/W plans, reproductions of the plans, and cross sections are transmitted to Land Acquisition from Design. After the graphics system is fully in use, the copies of the approved R/W plans will still be transmitted as hard copy, but the plans and cross sections will be obtained from Design electronically. The engineering staff of Land Acquisition will then add their features to their own layer of the plans. The "plan checking" process which precedes approval of R/W plans, will be made quicker and more efficient by the ability to transmit the "check plans" back and forth electronically. In addition, the survey data required by Land Acquisition will also be transmitted to them in electronic, ready to use form by the Survey Section just as it will be transmitted to the Design groups.

DISTRICT AND CONSTRUCTION. District personnel will use the system for the design of their projects. They will also make extensive use of the Road Inventory Database, as well as providing some of the information which makes up that database. Both District personnel and those in the Construction Section will perform an on station review of the plans for upcoming highway projects.

OUTSIDE AGENCIES. In the future, plans will be exchanged electronically with other organizations. The Design Consultant Services section will review plans on workstations which have been developed by the consultant engineering firms on their own graphics systems. Plans developed by county and municipal agencies for review by INDOT will be transmitted and checked electronically. The FHWA will also be able to examine digital INDOT plans. The development of the transmittal of electronic plans between agencies will occur fairly slowly and will depend upon the outside agencies migration to their own graphics systems and the compatibility between their systems and that of INDOT.

WHAT BENEFITS ARE EXPECTED TO RESULT FROM A GIS?

Within the context of INDOT applications, the distinction between CADD and GIS is even more than typically blurred. While bridge and road design are closely tied to traditional CADD functions, it is nonetheless essentially spatially oriented data. As such, these projects will feed from and add strength to a GIS. Therefore, when considering GIS benefits, those advantages arising from CADD can also be thought of in connection to GIS.

The primary tangible result of using the GIS will be increased productivity. Duplication of effort can be minimized at all phases of plan development. Specifically:

--Survey data can be collected with electronic data collectors, and any required checking or adjustment of the data can be performed by an individual in the survey unit on a workstation. The data will then be immediately useful to designers without further drafting required to produce preliminary plan sheets.

--When designers from different areas (for example, road and bridge design units) have projects in the same section of the road, they can share existing topography data and view each other's plan development work without having to re-draw any information.

--The designers will also be able to design project features and lay-out work directly on the workstation. The layout work will be directly useful instead of having to be copied by a draftsman.

--It is estimated that plan production will be increased in the range of 2:1 to 3:1. This has been estimated by evaluation of our plan development procedures, and checked by researching the improvements realized by other firms who have had experience with CADD and GIS.

--This increase in productivity will result in the development of more plans in-house with current staffing. Savings will be obtained by reduced expenditures on consulting fees.

--The ability to geographically tie together otherwise disparate projects, such as bridge maintenance projects, will help to provide a more intelligent approach to project planning. Construction mobilization costs, as an example, can be reduced by looking at bridge condition data from a geographic perspective.

In addition to these tangible benefits, a GIS is expected to bring other, intangible advantages. Some of these intangible benefits are:

--The designer will be able to more closely examine a greater number of alternatives. This will help provide the most efficient designs.

--Revisions to plans will be performed faster and easier. The revised output will also be more easily used.

--Use of the system will increase standardization of the plans appearance. This will aid construction personnel in use of the plans.

--The most up-to-date standard details will be readily available to the designers over the network. Copying a standard detail to modify for a special situation will be easier to do.

HOW MUCH IMPLEMENTATION HAS BEEN ACCOMPLISHED?

It was originally considered that the development of the Engineering System in Design would consist of five phases. These five phases can be described as follows:

Phase I - Phase I consists of initial installation of the system, establishment of system guidelines, and training of the CADD Unit Representatives.

Phase II - Approximately one third of the plan development personnel
III will be trained on the system in phase II. Upon
IV completion of their training, this group would begin to
work on plans electronically while another third would be
trained in phase III. The training of the final third
would be done in phase IV.

Phase V - This phase would provide workstations to those in design areas who review plans.

Phase I of the implementation plan has been accomplished. The system, including the VAX units, the workstations, the network, and peripheral devices are essentially installed. In addition, representatives from road design, bridge design, traffic design, survey, and standards have received training. This training included familiarization with the VMS operating system and instruction in the basic drawing program (GDS), the roadway design program (COGO/ROADS), and the ground modeling program (MOSS). Also as part of Phase I, directory structures and naming conventions were formulated for project files, GDS menus and menu programs were created or customized to fit the particular needs of INDOT, a library of standard symbols and linestyles was created and documentation of Phase I activities was accomplished.

As a result of the success of Phase I activities, it was decided to accelerate the implementation plan by combining the Phases II, III, and IV into two phases, each completing the training of one half of the plan department personnel.

THE PILOT PROJECT. WHERE DO WE BEGIN?

While progress is being made toward accomplishing the various phases of implementation, an effort is underway to concentrate on the more "pure" GIS capabilities of the system. Key individuals from Planning, Roadway Management, and Cartography, along with representatives from Information Services, have started to develop a Basemap Design and Implementation Plan. The creation of this basemap is essentially the pilot project for INDOT's GIS. The basemap will be constructed to provide GIS capabilities to Planning, Roadway Management, and Cartography, while at the same time providing a basis for expansion of GIS to the remainder of the department. While this is asking a lot from a pilot, preliminary analysis shows that such a plan is realistic.

The graphics portion of the basemap will be a road network that will likely be the result of USGS DLG-3 data that has been modified to include object names for homogenous road segments. These graphic road segments will correspond to records within the Road Inventory Database. The basemap will be considered complete and successful when queries can be initiated from either the graphics or the database side of the system.

WHAT IS ON THE HORIZON AND HOW WILL INDOT BE AFFECTED?

The current trend in this industry is for things to become more powerful in capabilities, faster in operation and generally smaller in size and cost. INDOT has chosen a system that is not based on proprietary hardware and is flexible enough to change with the times, yet not leave behind previous work.

The new directions we are now looking at include usage of Global Positioning System (GPS) services, combined raster and vector graphics, robotics, coordinated audio/video systems, remote sensing, automatic data capture and electronic transfer of information between systems. The district offices and supervisory staff will need to get involved in order to have access to project information for decision making.

On the social side of things, INDOT is actively participating in the development of a State Office of GIS through involvement with the Technical Task Force Committees, Advisory Resource Group and Mapping Policy Committee. Our in-house commitment is an indication of our interest in this new technology and our determination to make it work for us for all the benefits it may offer.

CONCLUSION.

The Indiana Department of Transportation has recognized the value of Geographic Information System Technology and has committed the resources, both human and computer, to the creation of a departmental GIS. Having acquired system hardware and software, INDOT is now going forward with an aggressive GIS implementation plan, that at a minimum, will change the way we think about transportation information, and will likely change the way we go about our day to day business. We have, indeed, begun to map the road to better infrastructure management through the creation and use of our own Geographic Information System.

LAND RECORDS MODERNIZATION IN WISCONSIN: BUILDING ON THE DANE COUNTY EXPERIENCE

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For more than a decade, cooperative research projects between the University of Wisconsin-Madison, Dane County (WI), and a variety of state and federal agencies have contributed to an understanding of the technical, institutional, and economic constraints to land information systems. The feasibility of a multipurpose, multiparticipant land information system based on "data custodians", implicit geo-referencing, and common data quality and exchange standards has been demonstrated for a variety of purposes including land records modernization and rural resources management.

In the late 1980s, a group of concerned professionals from a variety of local, state, and private organizations promoted state-wide legislation based on these general principals. In 1989, the Wisconsin Land Information Program and the Wisconsin Land Information Board (WLIB) were created. In the spring of 1990, a funding mechanism was created that will provide up to $6 million annually for local and state land records modernization activities. Counties will have direct access to a portion of these funds for qualifying activities, as specified in county-wide plans approved by the WLIB. Other funds will be available to local units of government through a grants-in-aid program administered by the WLIB. The WLIB has additional responsibility for coordinating the land and geographic system activities of state agencies, serving as a clearinghouse for digital spatial data and providing technical expertise for system development.

RURAL ADDRESSING AND GEOGRAPHIC INFORMATION SYSTEMS

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Abstract

Specifying the location of a rural residence is a common geographic problem. A combination of increasing numbers of rural residents and societal and technological changes that are providing more linkages between rural areas and urban service centers is prompting the need for rural addressing. Most addressing systems are designed for urban areas and are not applicable to rural areas. The mile marker addressing system meets all the requirements for a rural addressing system. With the addition of a geographic information system, rural addressing can be done efficiently and can provide the basis for a county's computer data base management system. Recommendations, which are based on experience in several New Mexico computerized rural addressing projects, are provided.

Introduction

Trying to find the location of a place of interest is a common geographic problem which most people experience. Knowledge of a location's address needs to be coupled with a set of directions to the site. In rural areas, problems exist because signs or other locational designations are infrequent and because addresses may not be linked to road names (e.g., P.O. Box or Rural Route numbers). Difficulties encountered in determining the location of interest result in increased time required to find a rural location. Increased response time for emergency service (e.g., fire, medical, or police) can mean the difference between life and death. More mundane services (e.g., cable T.V., phone service, or package/appliance delivery) may be limited or denied for rural areas because of the increased cost of locating rural residences and finding an efficient way to get to the location. In our society, local governments are primarily responsible for maintaining and disseminating an information base on the location of rural citizens.

Maps are the primary form of written communication used to relay information concerning locations. It is, of course, desireable to have the map information correspond with other written or oral forms of communicating a location (e.g., the address of a rural resident). Unfortunately, the addressing system used for mail delivery to rural residents does not necessarily give adequate directions to the dwelling. In many cases, mail delivery is to a cluster of mail boxes located at the intersection of two roads or to a box in the local post office (U.S. Postal Service, 1975). In some areas, and especially in the western United States, private companies that provide services to rural areas and local governments are working together to provide a new addressing scheme (Czerniak, et al., 1987; Gribb, et al., 1990).

An atlas, which combines in one source numerous thematic maps for a given region, is commonly necessary when dealing with large or complex areas. Atlases can be either electronic, where the information is stored in digital form and displayed on request, or the more traditional compilation of paper documents. A continuing problem for all governments is the need to maintain up-to-date information on the locations of its citizenry and the status of the available transportation network (i.e., keeping correct, current information in the atlas). When a new addressing scheme is being implemented, an opportunity exists for major changes in the procedures used by the local government for maintaining a geographic data base. One option, which is increasingly recommended, is the development of a computerized data base. A geographic information system (GIS) provides capabilities for creating, maintaining, up-dating, analyzing, and displaying locational information. Currently, there are numerous PC-based GIS systems that combine a data base for storing attribute information (e.g., age of the structure, brick or wood frame construction, number of residents, etc.) with output capabilities for either hard-copy maps or statistical tables. Generating the necessary revenues to accomplish this geographic information maintenance task can be a significant problem. Obtaining the necessary funds is usually more of a problem for governments with large rural areas under their jurisdiction because of the generally low tax base.

Rural Addressing

A comprehensive addressing system that includes the mailing address and the location of the dwelling with respect to the road network is needed for rural areas. Most addressing systems will meet the needs of urban environments (Corwin, 1978) and four methods are commonly used: street and avenue, the quadrant system, the baseline and grid system, and the century or mile marker system. The mile marker system, which is based on determining the distance of a dwelling from the designated road beginning, is considered most effective for rural addressing (Gribb et al., 1990). An advantage of the mile marker system is the ease with which distances between rural residences are calculated (Corwin, 1978). Selection of an addressing system is one of the first tasks associated with a rural addressing project.

A rural addressing project requires coordination of a number of groups, including the local government, the rural citizens, the postal service, and the local media for communication of project information to the rural citizens. Initially, the local government should assess the existing address data base and the associated maps. Once the necessary funds are identified and a decision is made to accomplish rural addressing, a meeting involving all concerned parties should occur. At this forum, the procedures that will be used in addressing the rural residents (e.g., the use of the mile marker system), the extent of the project (e.g., the types of questions that rural residents will be asked in the field survey), the time frame in which the work will be done, and the choice of either an electronic or manuscript (or both) atlas of rural residents should be identified and agreed upon. The choice of an electronic atlas, which is created using a geographic information system, is recommended for cost-effectiveness, reduction of data base maintenance problems, ease of data transfer to other groups, and standardization of output map scales (Gribb et al., 1990; Lam, 1985; Wunderlich, 1986). It is important to know enough about the entire scope of a rural addressing project and how a GIS can contribute to this process. If individuals with knowledge of computer mapping and GIS are not available within the local government, it recommended that a geography department at a nearby college or university be consulted for this expertise.

Computerized Rural Addressing and GIS

Once the decision is made to use computerized mapping for rural addressing, several aspects of the project must be determined. For example, the number and type of residence/road attributes that will be built into the data base needs to be identified and matched with the information that will be collected through the field survey of rural residences or obtained from other sources. A properly conceived rural addressing project will contribute to the work activities of both public and private agencies; the GIS data base can provide current information for bridge and road network maintenance, tax assessment, land use planning, county clerk record keeping, and utility companies (Emery, 1982). Since rural addressing is a major responsibility for a local government, county management personnel need to be aware of the costs/scope of the task and provide support for the activity. This administrative support is especially critical during the approximately two year period during the field survey and initial construction of the GIS data bases (Harrington et al., 1986).

There are a number of tasks that must be managed for a successful computerized rural addressing project (Gribb et al., 1990); these include (but are not limited to) the survey of rural residents, administration of project funds, acquisition of the necessary computer hardware and software, and the development of the GIS. In building the locational portion of the GIS data base, existing manuscript maps with consistent coverage information provide a logical place to start. Maps available through the US Geological Survey are frequently selected (Donahue and Faedtke, 1982; Harvey, 1986) because they can contain the Public Land Survey System (PLSS), which is considered crucial to development of a

GIS (Christman and Neimann, 1985). In several rural addressing projects in New Mexico, USGS 7.5 minute orthophoto quadrangles with the PLSS overlay were used as the primary map base for initial digitizing.

Two major types of information are entered into the GIS during data base development. The geographic base file (GBF) contains information about the location of the roads and the dwellings. In addition to the PLSS, the global grid system of latitude and longitude and the local state plane coordinate system are usually included. Including state plane coordinates should help insure a high resolution capability within the system and an ability to incorporate the detail of a new subdivision plat (Bauer, 1987). Information available on existing maps held within the county or acquired from the USGS or other sources should be entered into the mapping system prior to the field survey. During the field survey, the accuracy of the locational information can be checked/edited at the same time that the field survey is collecting information on the rural residence and its inhabitants. The second major type of information for the GIS is the attribute information collected through the survey. The attribute information and corrections to the location information are also entered into the computerized mapping system. Many individuals consider the GIS data base development to be the most costly aspect of the whole project. Since future decisions will be based on the information contained in the GIS, it is important to insure that accuracy is not sacrificed for short-term cost savings.

GIS Implementation: Problems and Recommendations

Unfortunately, words of wisdom from existing "experts" usually are at least partially ignored and experience becomes the necessary teacher. In using a GIS for rural addressing, there are many new tasks/concepts that need to be understood. Successful system implementation involves technology transfer from existing sources of knowledge to the local government. Factors that can contribute to difficulties include: the level of computer and cartographic expertise of the county personnel, the complexity of the GIS selected, differences between individual expectations and GIS capabilities, and the management structure of local government (Harrington, et al., 1986). In general, the lack of knowledge of microcomputer operations and the GIS software selected creates a major obstacle to successful technology transfer. For individuals in management positions, care must be exercised in explaining exactly what the computerized rural addressing system will be able to accomplish. There is a difference between the "black-box" conception, where all you have to do is push a few buttons and the correct map appears, and the technical-based reality of data entry, editing, more editing, analysis, and map output.

Considerable experience in establishing operational microcomputer-based GISs for rural addressing in New Mexico counties (Czerniak, et al., 1987; Gribb, et al., 1990; Harrington, et al., 1986) provides the basis for a number of recommendations:

1) individuals should be specifically assigned to accomplish the rural addressing project and their work schedules should be adjusted in light of the amount of time required.
2) at least two individuals should be assigned to learn how the GIS works.
3) county and management personnel need to be aware of system capabilities and limitations.
4) the county employees that will work with the GIS should receive enough training so that they feel comfortable with system operations. This training should include a review of the basics of cartography and computer mapping.
5) provide frequent demonstrations to local government leaders. It is important that they know the scope of the rural addressing task, including both the problems encountered and the successes obtained.

The adoption of GIS technology by a local government is an important step into the information age. Since the biggest cost involved in an GIS project is data entry, the choice of an initial GIS may be guided by ease of user interaction with the data entry/digitizing software. It is common for hardware and software to evolve during the lifetime of a rural addressing project. Thus, a PC-based approach will help keep costs lower over the full lifetime of the local government's needs for rural addressing.

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SHARING GEOGRAPHIC INFORMATION ACROSS ORGANIZATIONAL BOUNDARIES:

An organizational-managerial perspective

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Abstract: As development of geographic information systems progresses, and technical problems are overcome, new problems arise. One of the frequently mentioned problems is that of the need for information and data bases that may be housed in several organizations. This paper explores the organizational and managerial roots of difficulties in sharing data bases. Historically, a combination of organizational structure and operations has resulted in the fragmentation of work projects into individual tasks and growing powerlessness among manual and clerical. In contrast, such fragmentation of tasks tends to increase the power of knowledge workers and their organizations, since such workers and organizations often control information that is valuable because it is often both unique and indispensable. This paper identifies three means by which alliances may be formed and information may be shared: appeals to professionalism, coercion, and bargaining. I propose a theory based on the relative power of the participants to predict which of these three strategies will be used.

Introduction

One of the frequently mentioned problems in the continuing diffusion of geographic information systems is the need to integrate information and data bases that may be housed in several organizations. Historically, a combination of organizational structure and operations has resulted in the fragmentation of work projects into individual tasks, resulting in growing powerlessness among manual and clerical workers. In contrast, the fragmentation of tasks has quite a different result among knowledge workers, particularly those with technical expertise in critical areas. Knowledge workers may possess information that is extremely valuable because it is both unique and indispensable to particular applications. Under such circumstances, the developer or owner of unique and indispensable information possesses a key element of control.

In this paper, I shall argue that there are three key means by which inter-agency alliances are formed, and by extension, by which information can be shared: appeals to professionalism, coercion and bargaining. The strategy employed to achieve information sharing, I hypothesize, will depend primarily on the relative power of the organizations involved.

This paper begins with a discussion of specific aspects of organizational and managerial practices and their role in the fragmentation of information gathering and data storage that are critical to the development of geographic information systems. In particular, I discuss the importance of Taylorism on the one hand, and of Weberian concepts of the expertise and client\groups on the other. In suggesting a means to reintegrate the data, I discuss the literature on the formation of alliances, which we may understand as the organization of disparate groups to achieve a specific goal. Finally, I suggest a hypothesis to predict under what circumstances organizations will employ various strategies to effect information sharing, based on their power relative to that of other organizations involved.

Taylorism and the Principles of Scientific Management

An influential seminal work in the field of management is Frederick Winslow Taylor's *The Principles of Scientific Management.* Beginning with the premise that increased productivity bring lower unit costs, which are advantageous to employer, employee and customer (or client) alike, Taylor argued that "...the best management is a true science, resting upon clearly defined laws, rules, and principles, as a foundation" (1911, 1947:7). Furthermore, good management lies not with particular individuals, but instead resides in basic knowledge and skills that can be learned. Taylor coined the phrase "scientific management" to describe his theory of management.

The principle of scientific management calls for the development of a science to replace the "rule of thumb" knowledge of workers. The focus of scientific management is the task. As Taylor himself notes,

> Perhaps the most prominent single element in modern scientific management is the task idea. The work of every workman is fully planned out by the management at least one day in advance, and each man receives in most cases complete written instructions, describing in detail the task which he is to accomplish, as well as the means to be used in doing the work. And the work planned in advance in this way constitutes a task which is to be solved, as explained above, not by the workman alone, but in almost all cases by the joint effort of the workman and the management. This task specifies not only what is to be done but how it is to be done and the exact time allowed for doing it (1911, 1947: 39).

Within this general notion of the task idea is an explicit description of the "...subdivision of the labor; each act of each mechanic, for example, should be preceded by various preparatory acts done by other men. And all of this involves, as we have said, 'an almost equal division of the responsibility and the work between the management and the workman'" (Taylor 1911, 1947: 38).

Taylor's Principles of Scientific Management were widely accepted, both in theory and in practice, in Europe and the United States in the early part of this century. Urry

(1986) suggests, however, that the adoption of scientific management occurred more rapidly in the U.S. than in Europe, partly because "technological changes [had] outstripped the capacity of craftsmen trained in traditional techniques to organize production in the way they had in the past" (Urry 1986:46). Indeed, the implementation of scientific management techniques in the early 1900s was greatest in brand new industries, such as the automobile industry. One of the major contributions of Henry Ford, for example, was the implementation of the assembly line, which is wholly consistent with and may be perceived as an outgrowth of the principles of scientific management.

The implementation of scientific management has not been without consequences. One important consequence has been the growth in the power of management even as there has been a diminution of the power of labor at the lowest levels of the hierarchy (Lipietz 1986; Sayer 1986; Urry 1986). At the same time, however, Urry suggests that there has been an increase "... in the numbers and influence of industrial engineers..." and that their relationship with management has become "increasingly symbiotic" (Urry 1986:46). While Taylor's Principles of Scientific Management help us understand the origins of the fragmentation of tasks, Weber's theory of bureaucracy helps explain the growth in power among engineers and other professionals in spite of managerial tasking edicts.

The Weberian concepts of expertise and professionalism

Since it was first translated into English in 1946, Max Weber's theory of bureaucracy has become the keystone of organization theory in the United States. There are some important consistencies between Taylor's Principles of Scientific Management and Weber's theory of bureaucracy, such as office hierarchy and graded authority resulting in a firmly ordered system in which higher offices supervise lower ones. Another similarity is that the management of the office in a bureaucracy follows general rules that are more or less stable, more or less exhaustive, and that can be learned (Weber, in Gerth and Mills 1946).

In sharp contrast to the manual worker described by Taylor, Weber's bureaucrat is frequently trained or educated outside of the institution where he or she is employed, often at a college or university. This specialized training is often coupled with some sort of certification, such as the earning of academic diplomas (the Ph.D., for example) or the successful passing of professional examinations (the Bar Exam, for example). This coupling provides objective evidence that the individual has mastered specific professional skills.

Over time, the bureaucracy may come to occupy a position of considerable power within its jurisdictional sphere based on the expertise of its professional staff (bureaucrats). In the case of the public bureaucracy, the legislature (or some other body of elected officials) is -- nominally at least -- the 'master' of the bureaucracy. Yet the master rarely has the degree of expertise that the servant, bureaucracy, possesses. In practice, this means that the political master frequently plays the role of 'dilettante' to the bureaucracy's 'expert.' Particularly in the case of highly technical fields, the master often must defer to its more knowledgeable servant.

The related source of the bureaucracy's power is the professionalism of bureaucrats and their ability to guard their professional knowledge from outsiders. Each profession has a body of knowledge that is uniquely its own. In order to become a member of the profession, the hopeful candidate must go through a more or less well-defined right-of-passage that ordinarily culminates in some sort of certification process. For example, if a person wishes to become a lawyer, he or she attends an accredited law school, graduates, takes the bar examination, and -- provided he or she passes the exam -- is admitted into the practice of law.

The profession that can closely guard its body of knowledge improves its staying power. Technical professions are often very successful in this objective because they have learned to guard carefully a relatively small, but highly complex body of knowledge that is theirs. While limiting entry into the field, certification serves a valuable purpose in helping to preserve the technical credibility of the group within its field of expertise.

In contrast to the emphasis Taylor placed on management and control, Weber recognized the power inherent in professional expertise. In contrast to the manual worker, the expertise of professionals limits the absolute control of management. In fact, professionals in bureaucracies discover in some instances that it is to their advantage to use their expertise to control a very small part of a larger project -- especially if that small part is critical. Moreover, as recognized experts in their fields, bureaucrats are in a position to redefine their tasks, emphasizing the technical details and the expertise required. Unless management possesses equivalent or greater expertise, the bureaucrat-expert can maintain significant control over the work itself.

Fragmentation of tasks

Whereas scientific management promoted the subdivision of tasks within individual organizations, bureaucracy tends to subdivide tasks and delegate them to separate organizations. There are two reasons for the development of specialized bureaucracies, both of which are consistent with Weberian theory: expertise and client groups.

The notion of expertise as a requirement for public employment has become widely accepted and implemented, as evidenced by the slow demise of political patronage and its replacement with the Civil Service system as the predominant system for hiring government employees at all levels. The development of increasingly specialized academic programs of study and professional school programs reinforces this phenomenon by providing a ready supply of trained professionals. In some organizations, professional hegemony assures that only individuals with a specific degree, and sometimes from a limited group of institutions, find employment in a particular organization. This may occur intentionally as in the practice at General Motors Corporation of hiring engineers trained at its affiliate school, General Motors Institute. Or, it may occur unintentionally or coincidentally as a by-product of "old-boy networks," for example.

The expertise of individuals in the organization becomes part-and-parcel of the organization itself. As noted, this gives the organization tremendous authority within its area of expertise. The notion of expertise is so well accepted, in fact, that even the U.S. Supreme Court is loathe to overturn substantive agency decisions suggested by technical experts (Yellin 1981).

The second reason for the development of specialized bureaucracies is the linking of organizations with specific client groups. Each organization that comes into being has a specific mission or purpose. This mission or purpose is generally linked with some client group. For example, the U.S. Department of Housing and Urban Development was created to address the needs of the urban poor in the U.S., recent evidence of administrative malfeasance notwithstanding. Similarly, the Pentagon has a smaller number of very powerful clients within the U.S. military-industrial complex.

As increasingly specialized client needs come to light, new organizations arise. For example, the U.S. Department of Health, Education, and Welfare was reorganized by President Carter in 1980 into the Departments of Health and Human Services, and Education to better serve these very different client groups. The creation of new agencies, of course, also benefits the bureaucrats who possess the necessary credentials to assume positions within them. Moreover, the same interest that leads the bureaucrat to earn credentials in a specific field may also provide him or her with the motivation to perform to the best of his or her ability within the organization. The opportunities for career advancement also serve as motivation for the bureaucrat. In short, it is difficult to untangle the relative contributions of expertise and client groups to the development of specialized bureaucracies, although it is clear that both play a role.

Fragmentation of data

The combination of the subdivision of tasks and the development of increasingly specialized bureaucracies has as one of its consequences and corollaries the fragmentation of data. Even as government functions have been split among a variety of agencies, the agencies charged with specific functions have responded to their mandates by gathering information and data essential for the performance of their work.

It has become a truism that "knowledge is power." If this is so, then what of the components of knowledge, data and information? Again, the concept of professionalism is relevant. It is not uncommon for organizations to protect their knowledge, information and data bases as a means to exert their professional hegemony and demonstrate their expertise, which in turn facilitates the protection and expansion of professional turf. This can create a snowball effect, as those who control information use it to advance their knowledge, thus improving their expertise, which can fuel the cycle.

As long as the organization maintains control of valuable information, it can remain dominant and protect or even improve its professional position. Should the organization lose control, or should the information lose its value, the organization's position will weaken. The organization therefore has a strong incentive to maintain control of any information it possesses and use that control wisely.

The fragmentation of information and data is far different in its effects than the fragmentation of tasks. Whoever possesses valuable information needed for the completion of a larger task is valuable. The knowledge worker may possess unique and necessary information, and in this way may resemble more closely the last piece of a jigsaw puzzle. Even though the piece may be one of 1,000 pieces, its uniqueness makes it irreplaceable. In contrast, in many cases the work of the manual worker has been simplified to the point where he or she may be readily replaced, much as we purchase a new air filter for our car.

If we agree that the possession of information serves as a source of control for individuals and organizations, then we are faced with questions about the ways in which organizations can be induced to relinquish this control. The literature on alliances may offer some insight into resolution of this problem.

Information-sharing alliances

There are several bases for the formation of alliances, or intergovernmental systems as they are sometimes called. Olson and Zeckhauser (1969) and McGuire (1974) suggest that even when people (or organizations) are devoid of feelings toward one another (either positive or negative), they may find that it is in their interest to organize for the purpose of providing collective goods. Among the bases for the formation of alliances are professionalism, coercion and bargaining.

Appeals to professionalism may sometimes be a motivating factor in the development of alliances that can facilitate inter-agency information sharing. Milward (1982) and Keller (1984) note the importance of functional interests and professionalism in establishing intergovernmental systems. Gage (1984:136) argues for the importance of understanding such networks as "... instruments for establishing and maintaining political networks to accomplish policy objectives." In some cases, professionals may respond to a sense of professionalism, putting aside inter-agency rivalries to pursue a common goal. Such short-term sublimation of individual and agency goals to a larger picture can sometimes result in long-term benefits aside from the achievement of a specific common goal. Such joint ventures may stimulate employment opportunities in the field and foster consistent support for the agencies in specific policy areas.

In some instances, the development and maintenance of alliances will be far more difficult, depending on the negotiation of an acceptable exchange among the parties involved. As Weber asserts, "Rational exchange is only possible when both parties expect to profit from it or when one is under compulsion because of his own need or the other's economic power" (Weber, in Roth and Wittich 1978:73).

In general, intergovernmental systems (or networks, as they are sometimes called) are characterized by an uneven distribution of power (Lindahl 1919; Stern 1979; Milward 1982; Keller 1984). Within this environment of uneven power distribution, it is not unusual for factions to compete for power to assure that their goals are ultimately adopted and implemented by the intergovernmental system as a whole (Milward 1982:470). The result is an ongoing search for equilibrium among the members of the system (Milward 1982; Keller 1984). Equilibrium is not a static condition, but rather a process outcome that the members of the system achieve through their efforts to gain power. Inasmuch as the quest for power is ongoing, conflict arises as the equilibrium point for the system as a whole changes frequently.

While it seems to be inevitable, conflict should not automatically be viewed as a negative element (Pondy 1967; Buntz & Radin 1985). Rather, conflict is the means by which the intergovernmental network achieves an equilibrium of power. In some instances, conflict can produce negative effects; in others, it serves an important integrative function within the network (North, Koch & Zinnes 1960; Pondy 1967). Keller (1984:467) notes that members of the network may attempt to link their own organizational missions with the values held by powerful external groups as a means to improve their power position within the network. Pondy (1967:313) shares this view: "A major element in the strategy in strategic bargaining is that of attitudinal structuring, whereby each party attempts to secure the moral backing of relevant third parties."

A theory of information-sharing strategies

The literature on alliances suggests three separate ways in which inter-agency alliances occur: (1) appeals to professionalism; (2) coercion; and (3) bargaining. Appeals to professionalism may in some cases represent an appeal to somewhat altruistic, noble values. In other instances, such appeals may reflect crass self-interest on the professional level. An appeal to professionalism has as one of its advantages its very low cost. It is therefore readily available to any organization.

The second means by which inter-agency alliances occur is through coercion. In some instances, coercion comes by way of controls placed on a government by some more powerful level of government. For example, physical development projects of a certain size that are proposed as federally funded efforts are subject to the terms and conditions of the National Environmental Policy Act of 1969. Similarly, state governments may have the authority to require specific information of local governments.

In inter-agency networks where the power structure is less well defined, or where there is minimal difference in the power of the various agencies, coercion may be impossible. In these instances, bargaining appears to be the most likely means to achieve an agreement on the information.

Within the basic concept of bargaining, organizations have a variety of resources at their disposal. In some instances, information swaps may be possible. Some organizations may have the economic resources to purchase information from other agencies, or to provide some other considerations.

Two factors stand out as central to achieving agreements on information sharing: the value of information to the negotiating agencies, and the inter-agency power structure. Assessing the value of information continues to be a nagging problem. Information does not have value in and of itself, but rather its value is related to its utility to its potential users. One clear indication of the value of information is the price it commands in the market. The very existence of information brokerage firms provides evidence that market methods of valuation does occur. However, assessing the value of information held in the public sector remains an inexact art at best.

I argue that it is possible to identify on the basis of the balance of organizational power, which of the three types of resolution will occur (appeal to professionalism, bargaining, and coercion). Figure 1 on the following page identifies under which power structures each of the types of resolution will obtain.

This model assumes that agencies will seek the least-cost resolution. Within this model, the two least-cost resolutions are coercion and appeals to professionalism. Coercion, however, is available only to organizations that possess the power or authority to pursue it. Appeals to professionalism are available to everyone.

Where the balance of power favors the seeker of information, that organization may exert its authority and demand the information of the weaker owner of the information. Where the balance of power favors the owner of the information, the weaker seeker of the information has neither the authority at its disposal to demand the information, nor the power needed to enter into a bargaining situation. When the seeker of information is relatively weak, it must rely on appeals to altruistic notions of professionalism and the public good. Bargaining can occur only when both the owner and the seeker of information possess roughly equivalent power, although I hypothesize that it makes little difference if both are relatively powerful or relatively weak.

The presence of complicating factors, such as the value of the information and the relative power of the agencies involved, gives rise to uncertainty about the resolution of specific cases. Indeed, the relative value of the information in question to the agencies involved is likely to become part of the power equation. Again, because of the difficulty of accurately assessing the value of information, this contribution of the value of information to the relative power of the agencies is unknown.

Empirical study is needed to ascertain the validity of the model developed in this paper. Actual case studies of information sharing will be needed to gather this information. Case studies should yield valuable information about the nature of the inter-agency bargains agencies adopt to make possible the sharing of information needed for larger scale geographic information systems.

Distribution of Power and Strategies to Achieve Information-Sharing Alliances

		Owner of Information	
		Powerful	Powerless
Seeker of Information	Powerful	Bargaining	Coercion
	Powerless	Appeal to Professionalism	Bargaining

Figure 1

Conclusion

Current concerns within the GIS community about the problems of information-sharing will continue to grow as technical problems are resolved. It is useful to understand the managerial and organizational roots of this problem in order to discover ways to promote inter-agency information-sharing. Whereas Taylorism promoted the subdivision of workers' tasks by management, Weberian notions of bureaucracy suggests that experts may use their expertise to consolidate their professional niche. The size of the niche is irrelevant; it is the significance of the niche that is critical.

A discussion of alliances suggests that appeals to professionalism, coercion and bargaining, I argue, are the key means by which inter-agency alliances are formed. Which strategy will obtain in a specific case, I argue further, is a function of the relative power of the agencies involved.

Research in this area is needed. A combination of case studies and surveys should be pursued to test this hypothesis. At the same time, such studies may suggest specific incentives that may be used to elicit the cooperation of information-owners. Within the area of GIS, institutional issues will continue to play a role. It is hoped that this hypothesis will help shed light on issues related to institutional information-sharing.

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MACROS FOR REPETITIVE MAPMAKING FROM ARC/INFO COVERAGES

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ARC/INFO, a geographic information system (GIS) software package, can produce computer generated maps both interactively and as batch routines. Two macro programs, MAPMAKER and MAPINCH, were written to allow the efficient production of maps used to verify the accuracy of the digital data.

These macro programs are being used to produce maps that show the locations of Abandoned Mineland Project Sites. The information used to make these maps was produced in the first phase of construction of a GIS that will contain information about Indiana's coal mines. The units of some coverages (map layers) were in inches; the remainder had been converted to meters. These macros demonstrate how to produce identically scaled maps from different coverages.

The macros were produced as part of the Coal Mine Information System - Phase IV, which is 100 percent federally funded by the U.S. Office of Surface Mining Reclamation and Enforcement through the Indiana Division of Reclamation.

DIGITAL MAP INFORMATION ABOUT COAL MINES AT THE INDIANA GEOLOGICAL SURVEY

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Geographic information system technology offers the ability to view spacial relationships with the versatility of a database. As with any other database system, however, data must be entered into the system before any analysis can begin. Spacial data is much more time consuming to enter and check than is textual data, which makes an exchange of information about this type of data desirable.

This map of southwestern Indiana shows the current status of the conversion of map and database information of the Indiana Coal Mine Information System into ARC/INFO coverages. Three types of information are being converted: 1. locations of Abandoned Mineland Project Sites, 2. locations of underground coal mines, 3. locations of surface coal mines.

This project is 100 percent federally funded by the U.S. Office of Surface Mining Reclamation and Enforcement through the Indiana Division of Reclamation.

APPLYING REMOTE SENSING AND GIS TECHNIQUES IN SOLVING RURAL COUNTY INFORMATION NEEDS* by Chris J. Johannsen[1], R. Norberto Fernandez[1], Fabian Lozano-Garcia[1] and Jack Hart[2], Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette, Indiana 47907.

Introduction. This project was designed to acquaint county government officials and their clientele with remote sensing and geographic information system (GIS) products that contain information about land conditions and land use. The specific project objectives are:

1) to investigate the feasibility of using remotely sensed data to identify and quantify specific land cover categories and conditions for purposes of tax assessment, cropland area measurements and land use evaluation,
2) to evaluate the use of remotely sensed data to assess soil resources and conditions which affect productivity and
3) to investigate the use of satellite remote sensing data as an aid in assessing soil management practices.

Miami County, Indiana was chosen as the experimental site for this project (Figure 1). The Miami County Extension Agent, Jack Hart expressed an interest in using remote sensing and GIS products in his work. He arranged for other county officials to visit with LARS researchers and a proposal was developed and funded by the National Aeronautics and Space Administration. Other participants of their project are:

Greg Deeds, Miami County Office of the Surveyor,
Betty I. Craig, CED, Miami County ASCS Office,
Randall J. Moore, District Conservationist, Miami County Soil Conservation Service
Nancy Hardwick, Miami County Tax Assessor

Approach. Twenty-Eight square miles were selected randomly for development and evaluation of the satellite data analysis and the geographic information system. Fourteen out of the twenty-eight

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[2] Miami County Extension Service, Miami County Indiana

square miles are used in developing the analysis methodologies; the remaining fourteen sections are used to evaluate the land cover/land use classifications. Landsat and SPOT satellite data from 1987 and 1988 growing seasons were selected and land cover maps were classified from this data (Figure 2). Land ownership maps were obtained from the County Surveyor's Office and soil maps from the published Maimi County Soil Survey. The soil maps needed to be registered to the 7.5 minute topographic maps since uncontrolled photography was used as a base map. Both ownership and soil maps were digitized for the selected sections. Figure 3 shows the map information digitized for all sample sections.

Preliminary Results. The GIS approach used in this research is shown in Figure 4. The model takes into account temporal land cover information derived from satellite data through digital analysis, land ownership maps redrafted on a scale of 1:24,000, soil maps (originally published at a scale of 1:20,000) adjusted and redrafted at 1:24,000 scale, roads derived from USGS 7.5 minute quads, and drainage networks derived from the combination of USGS maps, aerial photography and soil maps. These maps are stored in the spatial database on a section basis. We have also designed two non-spatial databases (land ownership and soils) to store attribute data related to the maps. This is the subject of other paper being written by the authors.

With both, the spatial (maps) and attribute databases in place, it is possible to perform different kinds of analysis. Proximity analysis were used to calculate easements and right-of-ways for ditches and roads. Ownership, soils and land cover maps are combined using standard GIS functions to produce a final map that shows these three variables plus easements (Figure 5). Maps can be produced for a section, a farm, or the entire county if requested. Area calculations are done automatically by the system and the results are included in the tax form, along with information store in the attribute databases.

Future development. For the land cover/land use research, we will complete the analyses of all of the TM and SPOT data for all development and evaluation sites to assess differences due to soil and topography. Temporal analysis, to improve discrimination of land cover categories, will also be completed. Products of land cover/land use analyses, display of landownership information, soils database information and similar data will be shared with county officials, as well as the State offices of the Soil Conservation Service and the Agricultural Stabilization and Conservation Service. Actual use of the products will be monitored by the County Extension Agent who serves as a local liaison for the projects.

For the research on soil spectral properties and soil erosion potential, we will complete the laboratory analyses of additional soil samples. These results will be combined with the satellite data and used to predict soil erosion areas within the county.

As for the soil management research, we will further analyze the favorable results received to date concerning recognition of soils covered with crop residues. Models to predict erosion and phosphorous yield deposition will be developed and run. The correct discrimination among residue cover types is of primary importance to the success of these models. The ability to recognize different types of residue on the soil surface with Landsat TM data would greatly advance our abilities to assess soil erosion losses. The Miami County Soil and Water Conservation District and the Conservation Technology Information Center are especially interested in this information.

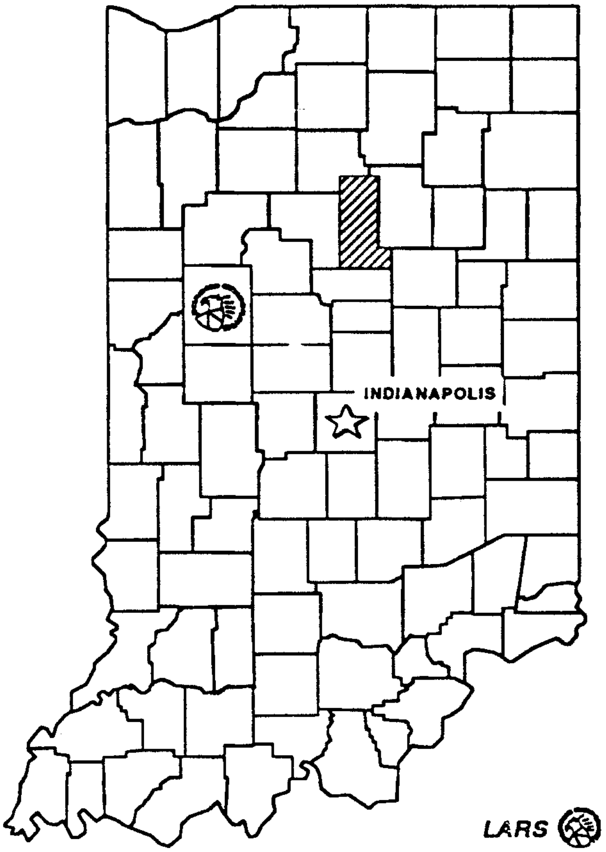
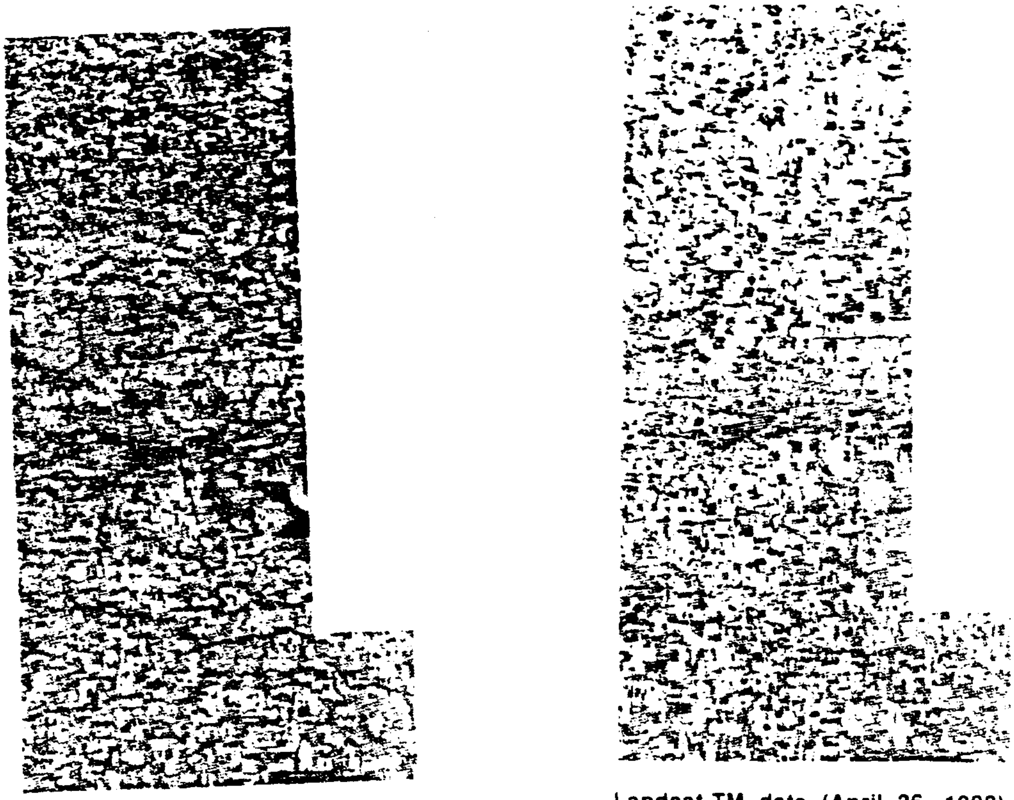


Figure 1. State map of Indiana showing location of Miami County.



Landsat-TM data (April 26, 1988),
TM-4=Red, TM-5=Green, TM3=Blue

Landsat-TM data (April 26, 1988),
Classification

Figure 2. Raw Landsat TM data map and a classification map for Miami County, April 26, 1988. Soil patterns are shown as low, medium and high contrasts and compare favorably with the soil maps of the county.

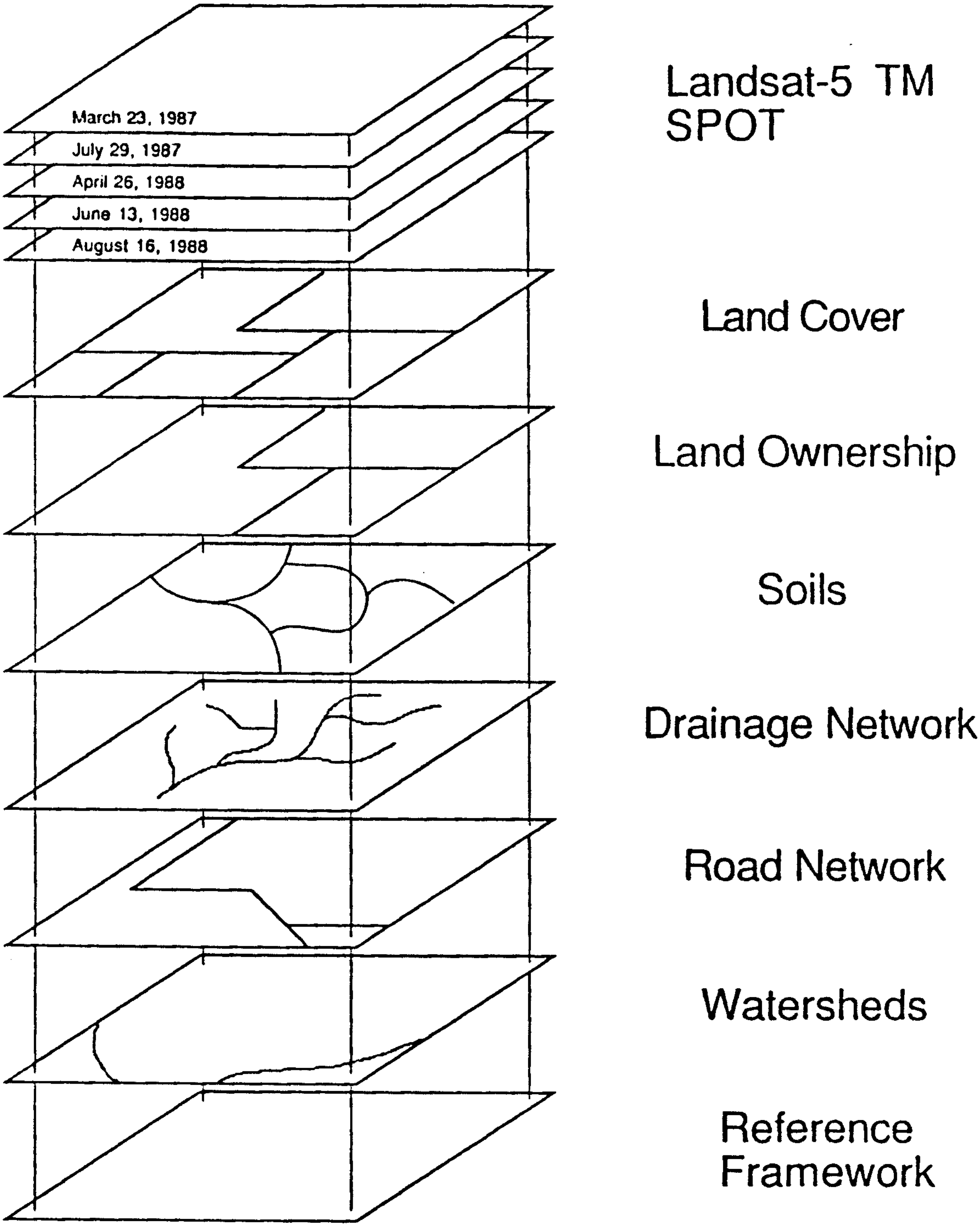


Figure 3. Representation of the spatial database of the geographic information system used in this study.

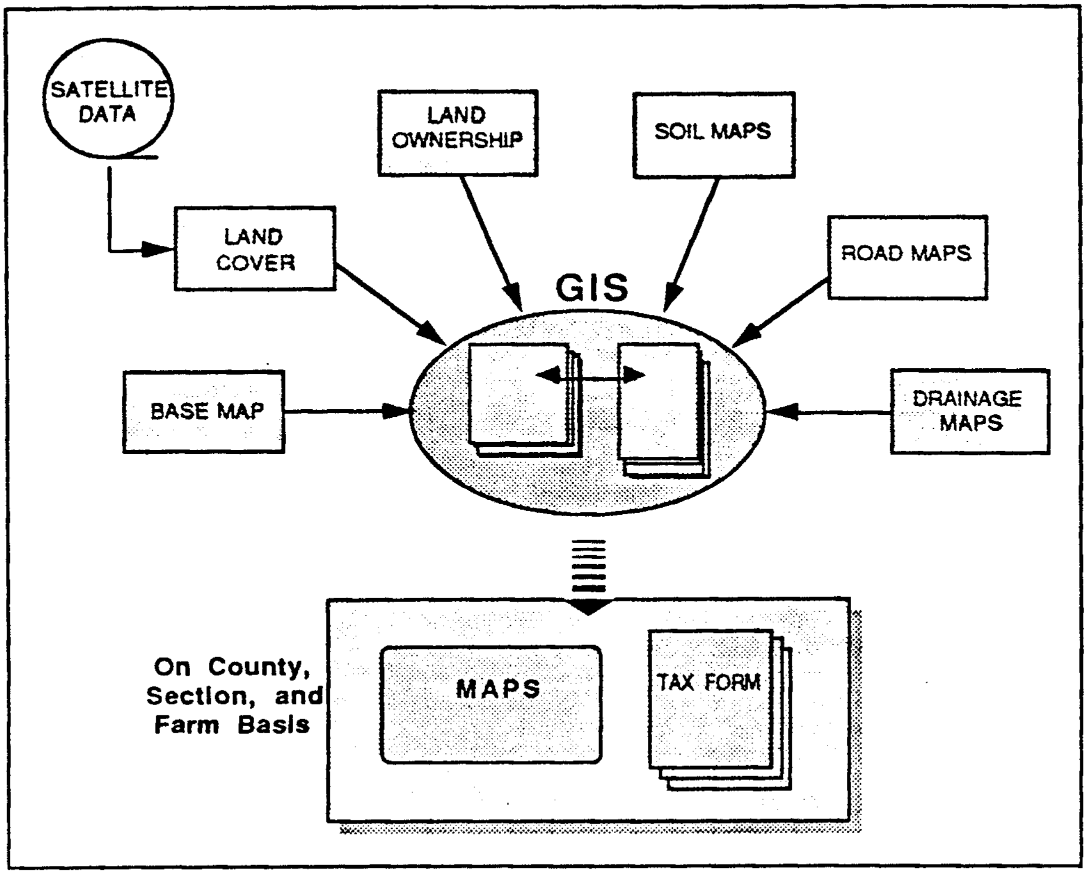
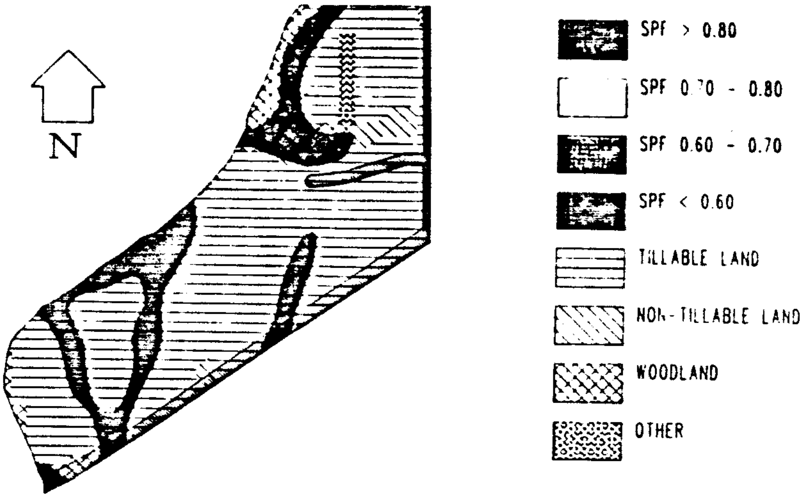


Figure 4. The geographic information system approach used in this study for agricultural reassessment.

SOIL PRODUCTIVITY AND LAND COVER

OWNER: John Farmer

LOCATION: Parcel 6 Sect 9,T28N,R5E



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                    LAND DATA AND COMPUTATIONS
--------------------------------------------------------------------------
LAND  SOIL ID  MEASURED  PROD   BASE  ADJUST. EXTENDED  INFLUENCE  TRUE TAX
TYPE           ACREAGE  FACTOR  RATE  RATE     VALUE     FACTOR    VALUE
--------------------------------------------------------------------------

 1     Cr        3.94    1.02    495    504    1.985      0.00      1,785
 1     FsA       2.99    0.77    495    381    1.139      0.00      1,139
 7     FsA       0.12    0.77    495    381       45      0.00         45
 1     MsB      15.67    0.81    495    400    6.268      0.00      6,268
 7     MsB       0.00    0.81    495    400        0      0.00          0
 1     MtC3     20.08    0.60    495    297    5,963      0.00      5,963
 2     MtC3      1.57    0.60    495    297      466      0.60        186
 7     MtC3      0.11    0.60    495    297       32      0.00         32
 1     MtD3      4.90    0.50    495    247    1,210      0.00      1,210
 1     Pw        2.18    1.11    495    549    1,196      0.00      1,196
 1     Sh        4.78    1.11    495    549    2,624      0.00      2,624
 2     Sh        2.06    1.11    495    549    1,130      0.60        451
 7     Sh        0.34    1.11    495    549      186      0.00        186
 9               1.00           3500           3,500                3,500


MEASURED ACREAGE   61.0                       TRUE TAX VALUE    22,200
--------------------------------------------------------------------------

 PARCEL ACREAGE :              60.00
 81 LEGAL DRAIN :               0.00
 82 PUBLIC ROADS:               0.85
 9 HOME SITES   :               1.00
 TOTAL ACRES FARMLAND =>                        58.15
 TRUE TAX VALUE                22,200
 MEASURED ACREAGE:              61.0
 AVERAGE TRUE TAX VALUE/ACREAGE:                 363
 TRUE TAX VALUE OF FARMLAND:                     21,108
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Figure 5. Map of one ownership showing information of soil productivity, land cover (as determined from satellite data) and easements.

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NEGOTIATING THE MAZE: THE LEGAL FRAMEWORK BEHIND A PUBLIC ACCESS POLICY

As geographic information systems (GISs) proliferate, municipalities, counties, and states are beginning to realize that they must develop policies governing public access to the systems and to the products and services which are produced from them. Development of these policies is not an easy task. The difficulty arises for several reasons. First, there are conflicting opinions as to what an access policy should be. Some believe that access to government information, for any purpose, at any time, is a fundamental right. Others take a more modest view of the citizen's right to government information, holding that the public has a right to information about government activities and decisions, but that the government should not be used as a free information clearinghouse for any and all requests for information and analysis. Questions regarding whether fees should be charged, and if so, to what extent, are also raised. Further complicating the issues are the complexity, power, and expense of the information delivery systems now required to manage and process government data efficiently and effectively.

In addition to the policy and technical questions which must be considered when defining public access to a GIS, legal issues must also be addressed. The analysis of the legal aspects of a public access policy is often complex because state constitutions, open records laws, records management and archive laws, statutes governing the rights of municipalities, the commercial code and statutes controlling municipal and state liability must be examined. In addition to those state laws, federal copyright law and sometimes the federal Freedom of Information Act (FOIA) must be examined. Court decisions and administrative rules also impact the development of a public access policy. Because the laws in each state are not the same, policies may differ from state to state.

Notwithstanding the difficulty in defining a public access policy, it is important to do so. The first reason why jurisdictions developing geographic information systems need to develop access policies is to maintain control over those systems. It is quite possible that GIS personnel may be inundated by requests for system reports, maps, and copies of the database once the public becomes aware that the resource is available. These requests may become so extensive that the agency is precluded from accomplishing its mission, in essence turning the agency into a service bureau for the public. In addition, GIS custodians may find themselves faced with requests for system output under the open records laws. If those requests are granted without qualification, the precedents thus established may preclude the development of a reasonable access policy.

The second reason why an access policy needs to be developed early in the GIS implementation process is to protect and preserve the economic value of the system. If a municipality so chooses, user fees may be charged for various products and services derived from the system. Those fees, while certainly not designed to be a means of paying for the entire system, may provide significant sums of money for system development or maintenance, or may provide sufficient revenues to slow the increase in revenues obtained through taxation. The access policy should preserve the economic value of the system for the government which developed it.

The key concept which must be emphasized is that each jurisdiction should have the right to decide for itself what it wants to do in terms of a public access policy. Each jurisdiction's choice may be different. One municipality may wish to impose a high fee for access to its GIS, and for products and services produced therefrom, in order to minimize or eliminate frivolous requests. Another jurisdiction may wish to develop user-friendly menus and install terminals in public offices so citizens may access the GIS on their own, thus reducing demands on staff. Yet another municipality may find it advantageous to share its data with other municipalities or counties to enhance the quality of public decision-making. No one policy is right or wrong, in and of itself. The only "right" policy is the one which is developed by a governmental entity after full consideration of all the factors required to meet its needs and the needs of its citizens. The purpose of this paper is to offer some guidance to municipalities as they try to find their way through state laws to devise legally defensible access policies. Only a few of the relevant state laws will be examined; this paper is illustrative in nature, and is not intended to be an exhaustive analysis.

Indiana law offers some positive support for a GIS access policy based on the imposition of fees for GIS products and services. It should be noted that a general principal of municipal law is that municipalities and counties have only the power expressly given to them by statute. Thus, they are generally prohibited from taking action unless there is specific legislative authorization for the action. That general rule makes the formulation of an access policy somewhat more difficult. However, in Indiana the law is exactly the reverse. The Indiana legislature has given municipalities a broad grant of power under which they may govern themselves as they choose. This broad grant of power will assist Indiana municipalities as they develop GIS access policies.

There are a few restrictions, however, on the power of Indiana municipalities to impose fees. If a municipality imposes a fee for regulatory purposes, for example, the fee may not be "greater than that reasonably related to the administrative cost of exercising a regulatory power." IC 36-1-3-8(5). Given this restriction on the imposition of fees, municipalities may wish to construct their access policies in terms other than "regulation" of access to the systems. An alternative to regulation may be a "service" or "user" fee, which is permitted under IC 36-1-3-8(6). The service or user fee may be "reasonably related to the cost of the service provided." If a county or municipality wished to impose fees for GIS products or services, presumably it could do so under the service or user fee provision of the statute. It should be noted that no case was found which interpreted the words "reasonably related to the cost of the service provided." This leaves open the possible challenge of a fee which may be thought to be not reasonably related to the cost of the service provided. It would be prudent for a municipality which imposes fees for GIS products or services to be able to justify those fees in terms of system development costs, costs of operation and maintenance, personnel costs, etc., so the fee may be supported if it is challenged in court.

In addition to examining laws governing municipal powers, the open records law must be analyzed to determine its impact on the development of a public access policy. It is important for GIS custodians to differentiate legitimate requests under the open records laws from requests for GIS products and services which should not be governed by the open records laws. In addition to making those distinctions, the Indiana open records law provides some excellent support for GIS managers.

IC 5-14-3-3(c) provides, in pertinent part, that:

> a public agency may or may not, in accordance with a nondiscriminatory uniform policy of the agency, permit a person to duplicate or obtain a duplicate copy of a computer tape, computer disc, microfilm, or similar or analogous record system that contains information owned by or entrusted to the agency.

In accordance with this statutory provision, a public access policy could contain a non-discriminatory policy under which copies of the GIS database could be made available. If a municipality were to impose a fee for this service, the fee could be based on the service fee provision of IC 36-1-3-8(6) discussed above.

In addition to the provision permitting a policy which allows distribution of copies of computerized databases, IC 5-14-3-4(b)(11) provides that "Computer programs, computer codes, computer filing systems, other software that are owned by the public agency or entrusted to it" are exempt from the provisions of the open records law. This is significant for two reasons. First, while it is debatable whether software should be classified as a "record" under open records laws, at least Indiana, while considering software as a record, has exempted it from the application of the open records law. This means that if Indiana governments or agencies develop software, they do not need to provide the programs to the public free of charge or at nominal fees, but may license them or otherwise make them available at market rates.

The second reason why this statutory provision is important is that a GIS may arguably be included within the ambit of the term "computer filing system." No definition is given for that term in the statute, but a GIS, being a complex information delivery system consisting not only of detailed databases of graphic and attribute data, also contains several kinds of software and hardware devices. If any of those component parts are missing, the system would be severely limited at best, or, more likely, non-functional. Because of the integrated nature of the GIS, it is in the nature of a complex filing system, and thus may not be subject to requests under the open records law.

One other topic needs to be considered. As is the case in many other states, Indiana has limited the use of the defense of sovereign immunity. This means that a municipality or county may be sued for its negligence in developing GIS products and services. Because of this possibility, any government entity wishing to enter the marketplace with these products and services should in some way shield itself from that liability. There may be a number of ways to attempt this, but it should be emphasized that none may be guaranteed to result in a defense verdict if a municipality is sued for damages arising from the use of its GIS products and services.

One legal tool which may be used with GIS products is the Uniform Commercial Code (UCC or Code). The UCC provides certain implied warranties for products sold under the Code, and also provides a mechanism for disclaiming those warranties. If the requirements of the Code are followed, a municipality may gain protection from loss to the extent a Court would sustain the disclaimer of those warranties.

The UCC does not apply to services. Therefore, it is essential that any services provided by or through the GIS be governed by contracts written expressly for the purpose. The contracts should require the purchaser of the services to waive any right to sue for damages caused by the municipality's negligence, and to limit as much as possible any damages which may arise under the contract. These waivers of liability are not always favored by the courts, and so they may not be enforced if a lawsuit were to be filed for damages arising from faulty GIS services. However, they should be included for whatever protection they might give, and for the potential they may have to discourage the filing of suits in the first place.

The purpose of this paper is to provide some insight into the complexities of the legal analysis necessary in the development of a GIS public access policy, and to demonstrate the need for close consultation with municipal and county solicitors in the development of those policies. It should be emphasized that this analysis was based on a very cursory review of a few of Indiana statutes, and a more thorough analysis by a licensed Indiana attorney may lead to different conclusions, interpretations, or recommendations. Notwithstanding those limitations, however, this paper presented the complex nature of the legal framework behind a public access policy, and that the legal framework cannot be ignored when the public access policy is developed.

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GIS TECHNOLOGY AND REAPPORTIONMENT

ABSTRACT

Article 1 of the U. S. Constitution called for an enumeration of the U.S. population so that the seats in the U.S. House of Representatives could be apportioned among the states. This demographic data must be interpreted geographically to determine new legislative districts in all states that have gained or lost a congressman. This data must also be interpreted in all states where there has been a population shift among any of the existing districts. The analysis required for redistricting is an ideal application of GIS technology, and it will be required at all levels of government, from federal congressional to local school districts. GIS technology will use data sets that have never been available before, yet these data sets will be vital to almost every GIS implementation in the 1990's. GIS-related issues include redistricting guidelines, data sets, and technology; how both the redistrictors and the GIS services vendors are responding to these issues; and where GIS-redistricting fits into the overall explosion of GIS technology.

REAPPORTIONMENT

Reapportionment is the re-allocation of U.S. Congressional Seats among the various states, according to the population of each. Article I, Section 2, Cl. 3 of the U.S. Constitution states "Representatives...shall be apportioned among the several states...according to their respective Numbers...The actual enumeration shall be made within three years after the first meeting of the Congress of the United States, and within every subsequent term of ten years in such manner as they shall by law direct." In order to accomplish this enormous task of locating and counting everyone in the United States, the U.S. Census Bureau turned to an information management technology that is based on spatial analysis. This technology that captures, manages, integrates, analyzes, and displays data by its location is called Geographic Information System (GIS) technology.

Although commercial GIS software is readily available, there is no commercial software that could manage the massive amounts of data and unique activities of census taking. In addition, the Bureau has special processing requirements that no commercial software can meet. Therefore, the Bureau wrote all of its own software to collect, manage, analyze and report the census data. The Bureau calls its new system TIGER: Topologically Integrated Geographic Encoding and Referencing System. Unlike GIS software which emphasizes user interaction with the data, the Bureau software concentrates on automatically producing maps without human intervention. This is necessary in order to efficiently produce the many millions of maps the Bureau must produce. Although the Bureau's software is fully automated where necessary, it does have interactive capabilities where appropriate. For several good technical and legal reasons, the TIGER system is not available for use by the public. The TIGER system also only contains geographic data; the Census Bureau demographic data is not stored in the TIGER data base.

The information that the Census Bureau captures must be provided to the president by December 31 of the census year. The president is required to report the reapportionment, determined by the "method of equal proportions," at the beginning of the 1991 Congressional Session. If this paper were limited to GIS technology and reapportionment, it could end here. However, the same data that determines the reapportionment of congress can also be used to help determine the boundaries of the new legislative districts that must result from the reapportionment. Additionally, because the constitution has been interpreted to mean that all congressional districts, not just new ones, must be as nearly equal in population as possible, the reapportionment data can be applied to redefining all congressional districts so that they are equal in population. And, as a result of the U.S. Voting Rights Act, all other election districts also need to be equal in population. In order to create the equality in population, the boundaries of these districts must be redrawn.

While the reallocation of the congressional seats is called reapportionment, the redrawing of the district lines is called redistricting. While reapportionment is a straight forward mathematical calculation once the the population is known, redistricting is a technically complex, extremely emotional process. It is definitely worth expanding this paper to discuss redistricting, not just reapportionment.

POLITICAL CONSIDERATIONS IN REDISTRICTING

Most applications of GIS technology require a trade-off between unrestrained technical solutions and economical limitations, with the underlying organization issues providing direction and control. However, in political redistricting, the major issues are the political and legal considerations. The true goal of every redistricting process is not technically perfect districts, but rather the election of a politician. The results must also be able to satisfy state and federal laws. GIS technology will be used to justify human decisions, not to make those decisions.

LEGAL CONSIDERATIONS IN REDISTRICTING

While the subjective political forces take precedence over the objective technical issues in redistricting, the next most important issues, the legal ones, are also subjective. They rely on the human interpretation of a very complex set of laws. In fact, the first legal question is always "What is a justiciable issue?" That is, when there is an objection to the politically motivated redistricting process or results, can the courts even intervene? Even when it is determined that the courts can intervene, each redistricting problem is decided upon a case by case basis that considers the "totality of circumstances."

While it is, therefore, impossible to definitely predict what will be ruled proper and what will be ruled not proper redistricting, the following concepts are usually considered. Note, however, that there have been exceptions to every one of these following statements.

- The process must use Census Bureau data, both the Census Bureau maps and demographic data, either in paper or computer format.
- The districts should be as equal in total population, not voters, as possible.
- Communities of interest should be protected and city boundaries should be honored.
- New districts should preserve state interests, such as county boundaries, etc.
- Minority interests must be honored and challenges by minorities need only prove a discriminatory "effect" rather than an intent to discriminate.

- Goals of both 60 and 65% minority populations in a district, in order not to discriminate against the minority candidate, have been suggested. A larger percentage may indicate "packing" and a smaller percentage may indicate "fracturing," both of which are considered reasons to invalidate a redistricting plan.
- Redistricting may or may not group blacks and Hispanics together, depending upon whether they vote as a block or not.
- Multimember districts may be considered discriminatory.
- Compact and contiguous districts are considered appropriate.

Some of these requirements are conflicting. All are open to interpretation. None have a purely technical solution. There may be no solution that can meet all of the requirements.

ADVANTAGES OF COMPUTER-AIDED REDISTRICTING

The most important reason for using computer-aided redistricting (CARD) may be that there is too much data to analyze any other way. In June of 1990, the Census Bureau estimated that the map data required for Indiana alone would require 1,947 county block maps or 352 megabytes of data. The demographic data from the Census Bureau was estimated at 97 megabytes of data or 8,400 pages of computer printout. While the Census Bureau will supply all of this data in computer readable format, it will still be a technical challenge to load and integrate the geographic and demographic data sets into the computer. Added to this data from the Census Bureau is the election returns for the last ten years and lists of registered voters, also disaggregated to the block level, and computer assistance is the only method practical. All of these data sets and more must be integrated for consideration by a redistricting plan.

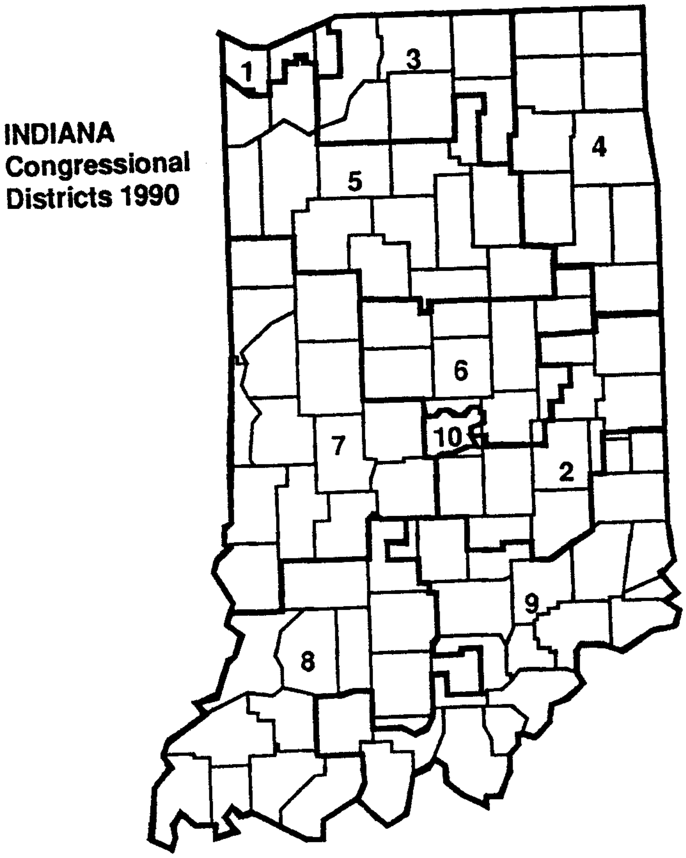
As a result of the massive amounts and different sources of data, it will take experienced computer users to prepare all of this data for computer-aided redistricting. Some redistrictors will acquire or hire the manpower to preprocess these data sets. For those who do not want to do it themselves, there are efforts being made both by private vendors and by some state governments to provide this information. As a result, there will be data sets that have been corrected and integrated with state funding. There will be equivalent data sets that have been purchased with partisan funding and are not publicly available, yet are being used to redistrict public offices. Public access to these data sets will be requested. Access is another issue that will be settled in the courts in the 1990's.

However, once the information is captured and ready to use, it again will be under the control of the politicians. Not only must all of the concerns mentioned in the previous paragraphs be considered, but the accuracy and detail must be precise.

AN INDIANA EXAMPLE

One of the best examples to show the problems of computer-aided redistricting, access to data, and the confusing and contradictory redistricting process itself, is here in Indiana. After the 1980 census, the Indiana General Conference Committee used a computer firm controlled by the Republican State Committee for redistricting (see Figure 1). Members of the Democratic Party and the public were not informed about the computer program, nor were public hearings conducted. Two days before the end of the session, the committee released its plan which was adopted by a party line vote in both Republican-dominated Houses of the General Assembly. Members of the state Democratic Party contested the plan in federal court for denying them equal rights under the law (Davis vs. Bandemer, 478 U.S. 109).

Figure 1



Although the plan was under litigation, the 1982 election was conducted using the contested plan. In the Senate, the Democrats won 52% of the Senate seats with 53% of the vote. In the House, the Democrats only won 43% of the seats, although they had 52% of the votes statewide. However, in multimember House districts, the Democrats had 47% of the vote but only won 14% of the seats.

The first question that the court had to answer was whether political discrimination was justiciable. The court not only said yes to that question, but also said that the court could look at the legislative process by which the challenged plan is adopted. Also, given limited access, lack of hearings and effect on preapportionment process, the plan would have been unconstitutional. However, the court ruled that one election was insufficient to prove unconstitutional discrimination and let the plan stand.

The final (so far) chapter in this story is that in spite of this so-called biased plan, Indiana, has two Republican U.S. Senators, a Democratic edge in the U.S. House, and both bodies of the state legislatures are within one seat of being evenly divided.

The results of Davis vs. Bandemer indicate that it is now legal to challenge on political party discrimination and to challenge on lack of public access and input. This sets precedents for challenging 1990's redistricting plans that did not exist in 1980. However, in spite of a theoretically successful challenge, the so-called discriminatory plan was upheld. And in spite of a so called discriminatory plan, the political party that drafted the plan did not gain a dominant position of power as a result.

From a computer-aided redistricting perspective, this example shows how it is possible to use a computer to redistrict and still fail to accomplish political goals; how it is possible to use a computer to redistrict and still be challenged in court; and how it is possible to use a computer to redistrict without sharing access with the public, even though the court says this is wrong.

GERRYMANDERING AND REDISTRICTING PRECISION

Computer-aided redistricting should make it possible to have districts almost equal in population and as compact in size as possible. The compactness requirement should prevent the drawing of elongated and misshapen districts, such as the one in the bill that Governor Elbridge Gerry of Massachusetts signed in 1812 (see Figure 2).

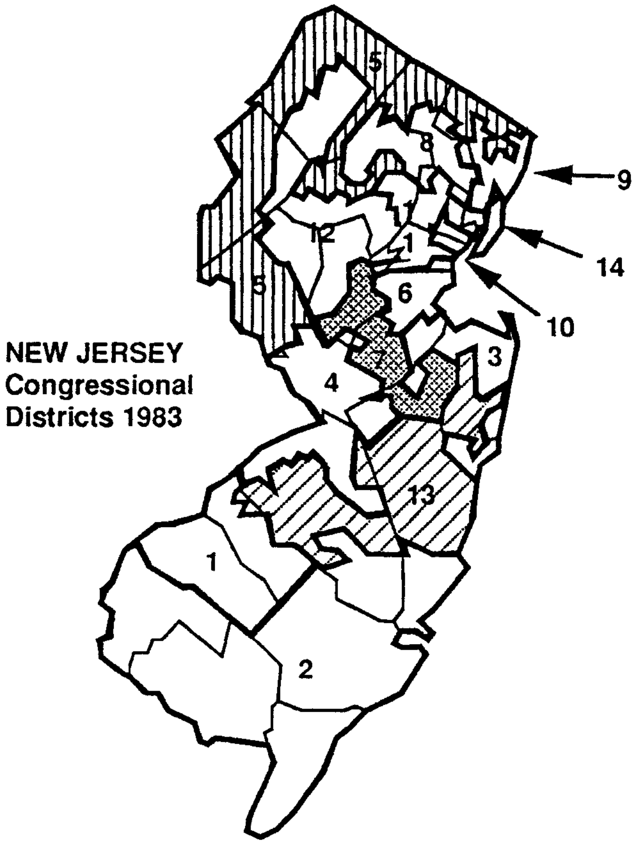
Figure 2

The Gerrymander
1812

That district near Boston was so misshapen that a political cartoonist, by merely adding feet, beak and wings to the mapped outline of the district, created a drawing of an unusual winged-salamander creature that was soon named a gerrymander. However, the New Jersey Democrats created even more unusual district "creatures" after their 1980's redistricting (see Figure 3).

Although the shapes of New Jersey districts resembled a swan (District 5), a fish hook (District 7), a chewed-up rabbit (District 13), and a football running back (District 9), the districts overall had a population range difference of less than one percent. In a state with over 7 million people and only 14 districts, the average difference was 3,674 people. Like many other state plans, this one was challenged (Karcher vs. Daggett).

Figure 3



The surprising result was not that the challenge was upheld, but that it was upheld because of the population variations between districts. The gerrymandering was not an issue. Another plan had been submitted with even less variance. The new plan also eliminated all of the gerrymander "creatures."

From a computer-aided redistricting perspective, the important computational role that computers can play is to assure that district populations are as equal as possible. And, given the advances in computer-aided redistricting since the New Jersey court ruling, this may mean that there is no plan with a population variance that couldn't be challenged on those grounds.

REDISTRICTING SCHEDULE AND ACTIVITIES IN INDIANA

Unlike the 1980 redistricting when Indiana had to deal with a change in the number of districts, the 1990 plans will only have to consider population shifts, which have not been significant. However, there still are challenges. The first is the amount of time that is allowed for the redistricting process. Redistricting cannot begin for real until the Census Bureau releases the population figures in early 1991. Given that starting date, one of the states with the shortest deadline is Indiana. If the legislature fails to meet an April 30, 1991, deadline, a redistricting commission, including a representative of the governor, will draw up a plan that will be law until the next session of the legislature.

The other challenge results from the actual counting of the population by the Census Bureau. The Bureau has been charged in court with undercounting certain groups, predominantly minorities and city dwellers. As a result, the Secretary of Commerce is evaluating the results of the Census and may choose to adjust the final result to eliminate the undercounting of those groups. The deadline for that decision is July 15, 1991, which is after the Indiana redistricting target date. If the Secretary decides to adjust, Indiana may have to redistrict again to account for the population changes.

VOTING PRECINCT REDISTRICTING

The next step in the redistricting process, after the legislature or committee has drawn the legislative districts, is the creation of local election districts and the smaller voting precincts. This work will be done by local governments. While it may not be as politically oriented as the state level districting, it requires much more actual work. Not only must more local district and precinct lines be drawn, but all the polling places must be identified according to the new precincts. Also, all the voters must be informed of their potentially new precincts, districts, and polling places. All this must be done using the election district boundaries supplied by the state, and must be completed well in advance of the next set of elections.

OTHER LOCAL GOVERNMENT REDISTRICTING

While the local governments may be severely challenged to create an operational redistricting system, they may find many unexpected benefits from the process. The technology and data sets used for the redistricting activity can also be used in many other local government departments. Additional data, supplied by the Census Bureau later in 1991, will include information on the location and ages of children that can be used for school districting, planning, and school bus routing. The other data sets available from the Census Bureau will be invaluable to planning departments because it will provide detailed information on the people in the town and county. If the local government already has a GIS, the redistricting data can be added to increase the usefulness of that system. If the local government has not yet acquired a complete GIS, the redistricting data maps can provide a basic structure for a number of activities, such as traffic analysis, emergency planning, vehicle routing, incident tracking, and rudimentary mapping. Just as important for a locality without a complete GIS, the redistricting system can provide GIS experience that could grow to the capability of a complete government-wide system.

COMMERCIAL DISTRICTING

This technology will continue to improve for several reasons. The private sector is realizing that it can use this same technology and data sets for product research, advertising, marketing, site selection and vehicle routing. The functionality of this technology can, and already is being exploited by the leaders in the commercial markets. While the potential state and local customers for this technology are numbered in the thousands, the potential users of Computer-Aided Sales and Marketing will number in the millions. The present vendors of this technology certainly realize this. While they are leveraging the immediate need of this technology for redistricting, it is the commercial market that they are truly pursuing.

The need to redistrict will introduce this technology and the new opportunities it brings with it to many government and political groups across the entire country. The irony to the growing political, legal, and commercial interest in redistricting data and technology is that the general public itself, who will be effected by this process and technology, historically has had no interest in the redistricting process.

Runoff, Erosion and Chemical Movement Simulation Using GIS

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Introduction

Preserving and maintaining the environment and natural resources such as soil and water are important concerns as an ever-increasing world population increases the demand for food and for living space. Many land management practices have promoted the degradation of once productive land and water. Excessive soil erosion due to water and degradation of water occurs on significant amounts of land in the United States and throughout the world. Erosion causes concern from the standpoint of resource conservation, deposition effects, and water quality. Erosion increases crop production costs (and ultimately food costs) due to fertilizer displacement, pesticide displacement, and damage to crops. It also reduces soil productivity as topsoil is removed faster than nature can replenish it. The sediment resulting from erosion degrades the quality of water and often transports chemicals that may cause harm when carried away from the intended point of application. Deposition of sediment in ditches, streams, canals, reservoirs, harbors, and other water conveyance structures reduces the capacity of these structures and requires costly removal. Damage from soil erosion alone is estimated to be in the tens of billions of dollars each year in the United States (Committee on Conservation Needs and Opportunities, 1986). Considering damage from other non-point source contaminants would push this estimate much higher as would considering damage for the rest of the world. Clearly, there is a need to protect our soil and water resources.

Several technologies have been used to assist decision makers with the management of soil and water resources. Simulations and expert systems (ES) are two of the technologies that have been used to analyze the effects that different management practices have on soil erosion, sedimentation, chemical movement, water quality, or crop productivity. Several models have been developed to study erosion and nonpoint source contamination of water and to assist in land use planning and natural resource management. However, the use of these tools has been limited. The primary reasons for their limited use are the time, expertise, and expense that are necessary to provide proper input data. ES can provide the help and expertise needed to operate these models. Simplification of data collection and input procedures for these models is needed, if they are to be fully utilized. Another technology that is beginning to assist decision makers with environmental management and with data collection and storage is Geographic Information Systems (GIS). To maximize the effectiveness of these technologies, environmental decision support systems that integrate these technologies are needed.

This paper examines an integrated system that consists of a non-point source pollution model (ANSWERS) and a GIS tool (GRASS).

ANSWERS

ANSWERS (Areal Nonpoint Source Watershed Environmental Response Simulation) was developed to simulate the behavior of watersheds having agriculture as their primary land use (Beasley, 1977). ANSWERS is capable of assessing the effects of land uses, management schemes, and cultural practices on the quality of water leaving a watershed. Its primary applications are watershed planning for erosion and sediment control on complex watersheds, and water quality analysis associated with sediment associated chemicals. It is written in FORTRAN and runs on several classes of computers including PC's.

ANSWERS is unlike many watershed models in that it is an event oriented model (versus continuous or long-term). Thus, it predicts watershed behavior during and immediately following a rainfall event and is primarily limited to a single storm. ANSWERS uses a distributed parameter approach rather than the lumped parameter approach that has been used by many watershed models (Beasley et al., 1980). A distributed parameter modeling approach is usually more computationally intensive than a lumped modeling approach, but its advantages often offset this disadvantage. A distributed parameter watershed model is able to incorporate the influences of the spatially variable controlling parameters (e.g., topography, soils, land use, etc.) in a manner internal to its computational algorithms. The primary advantage of a distributed parameter model is its potential for providing a more accurate simulation of the system being modeled. For watershed models, a second advantage of this modeling approach is its ability to simultaneously simulate conditions at all points within the watershed. This allows simulation of processes that change both spatially and temporally throughout the watershed. A final advantage of this approach is the ability to incorporate relationships developed from "plot-size" studies to make predictions on the watershed scale.

ANSWERS consists of a hydrologic model, a sediment/transport model, and several routing components. The conceptual basis of the hydrologic model was developed by Huggins and Monke (1966). The hydrologic model considers rainfall interception, infiltration, surface detention, and surface retention. The governing equation for the simulation of erosion is the continuity equation used by Foster and Meyer (1972). The erosion component describes the processes of soil detachment, transport, and deposition.

A watershed that is being modeled by ANSWERS is first divided into a series of small independent elements. In each element, the runoff and erosion processes are treated as independent functions of the hydrologic and erosion related parameters of the element. Outflow from each element is directed to other elements. The composite runoff hydrograph for the watershed and hydrographs for each element are determined simultaneously for each time increment. The solution process and updating of element data are continued until the watershed hydrograph has been completed or the end of the simulation period is reached.

All component relationships in ANSWERS are modular, thus facilitating modification and/or replacement of components (e.g. interception, infiltration, erosion) without adversely affecting other relationships. This framework allows appending of additional descriptive relationships to simulate other processes, such as chemical transport, as has subsequently been done (Beasley and Huggins, 1982). The general structure of the model was influenced by the need to model individual watershed components and their effects on adjacent components (Beasley and Huggins, 1982). Each of the physical processes are represented as an independent subroutine.

The ANSWERS data files contain information on topography, drainage networks, soils, land uses, and best management practices. Table 1 indicates the cell inputs that are needed. These data are normally taken from USDA-SCS Soil Surveys, land use surveys, cropping surveys, aerial photos, USGS topographic maps, and best management practice implementation data. Data can be entered in either English or metric units. Because of computational time and input preparation time requirements, watershed size should be limited to approximately 10,000 hectares. The size of elements typically ranges from 1 to 4 hectares.

Cell location	Slope percent and direction
Surface roughness	Drainage channel information
Antecedent moisture	Infiltration rate
Drainage response	Storage characteristics
Erodibility (USLE K)	Crop type and management
Maximum roughness height	Best management practices description
Storage characteristics	Relative erosiveness of a land use

Table 1. ANSWERS Cell Inputs

A variety of output data are produced by ANSWERS. The output data can be reported in either English or metric units. Limited graphical output is also available to provide a better understanding of the input and output data. The output includes: rainfall, runoff, and sediment yield hydrographs for the total watershed; individual element sediment loss/ deposition and chemical movement masses; and channel element deposition.

ANSWERS is able to estimate erosion and sediment yield distributed in time and space for single events. The use of small elements to describe the watershed allows it to represent a variety of land uses, soils, and topographic features. However, the building of input data files and the interpretation of the results requires significant amounts of time and requires someone who is knowledgeable of the model and its operation.

For additional details concerning ANSWERS, consult Beasley et al. (1980) and Beasley and Huggins (1982).

The Role of GIS

GIS have been used for a variety of applications. There are different ways of describing what a GIS is and what it does. One is to consider it a database (realizing of course that it is much more) that can be utilized by various models and tools. A single GIS for non-point source pollution control can have multiple applications: effectively pinpointing areas where resources are threatened, helping impartially distribute incentives and regulations used for rural land management, providing quality information to decision-makers cost-effectively, and speeding the delivery of conservation services.

One function of many of the GIS that have been developed to date is erosion control planning. Simple erosion prediction models such as the USLE (Wischmeier and Smith, 1978) are easily implemented within most GIS tools. Layers of data within the GIS are used to represent values of each of the factors of the USLE. A map showing erosion amounts or erosion potential is developed by simply multiplying the values in each layer together. Several researchers have implemented the USLE within a GIS for their study area. Ventura et al. (1988) developed a GIS for locating areas in which excessive erosion was occurring by implementing the USLE through GIS data layers. Conservation programs could then be targeted at these areas. It has also been used for such diverse applications as comparison of agricultural land assessments, examination of the environmental impacts of private sewage systems, comparison of land subject to regulation versus land receiving tax incentives for resource protection, examination of tax assessment class versus zoning category, and subdivision siting and lay out. Hession and Shanholtz (1988) also implemented the USLE with their GIS to estimate erosion potential.

Integrating Agricultural Non-Point Source Pollution Models With GIS

To date, few agricultural non-point source pollution models have been linked to GIS. There are several reasons for this. First, GIS technology has only recently advanced to a state that it is widely viable. Second, computational capability of commonly used computers for agricultural applications has only recently reached a point that can support the demands of GIS and distributed parameter models. Distributed parameter models are computationally and data intensive and thus are best suited to use the capabilities of GIS. The number of distributed parameter models for simulating agricultural non-point source pollution is limited. This is because of their limitations that have only recently been overcome.

There are several examples of agricultural non-point source pollution models that have used GIS-like tools. The work by Beasley (1977) to develop ANSWERS used an approach similar to a raster-based GIS for describing parameters used in simulating a watershed's response to a rainfall event. The development of AGNPS by Young et al. (1987) is also similar. Heatwole et al. (1986) developed a basin scale model by modifying CREAMS. It divides the basin into grid cells similar to ANSWERS. The model was used to evaluate the effectiveness of proposed best management practices (BMP's) near Lake Okeechobee in Florida. Onstad and Otterby (1982) implemented the USLE in a cell-like fashion for watershed areas to examine the impacts of cropping, tillage, and erosion control practices for several watersheds. Khanbilvardi and Rogowski (1984) used a grid to implement the USLE and a sediment transport model for two watersheds. Peralta and Killian (1987) developed a decision support system for examining groundwater planning strategies. Areas to be evaluated are divided into finite difference cells. In all these instances, the user describes the spatial variability of a watershed's parameters in a format compatible with the specific software rather than extracting the required input data from a GIS.

Jett et al. (1979) were among the first to describe the role that GIS could play in the hydrologic modeling of agricultural watersheds. They presented examples of ADAPT (Area Design And Planning Tool) applications that included the areas of hydrology, water resources, and wastewater management. Wolfe and Neale (1988) describe their efforts to use a GIS to reduce the data preparation time for a distributed parameter runoff model. Data preparation time is a severe limitation in the use of a distributed parameter model. They used the GRASS GIS to generate data sets for the FESHM model. Hodge et al. (1988) describe their efforts to link the ARMSED watershed model with the GRASS GIS. The ARMSED model is the U.S. Army version of MULTSED. The model estimates runoff, sediment yield, and sediment characteristics for rainfall events.

Hession et al. (1989) extracted data from a GIS to operate the AGNPS model. They evaluated best management practice (BMP) scenarios for several watershed areas in Virginia. Zhang et al. (1990) linked a solute transport model with a GIS to assess the potential groundwater impacts of common agricultural chemicals for an Oklahoma watershed. Smith et al. (1990) estimated runoff and flood levels for a small watershed, and displayed the flood levels using a GIS. Halliday and Wolfe (1990) implemented a GIS-based decision support system that used DRASTIC and other models to assess the groundwater pollution potential from fertilizers in Texas. Evans and Myers (1990) also implemented DRASTIC in a GIS to evaluate regional groundwater potential.

The GRASS GIS

GRASS (Geographical Resources Analysis Support System) (U.S. Army, 1987) was designed and developed by the Environmental Division of the U.S. Army Construction Engineering Research Laboratory (USA-CERL), Champaign, Illinois. There are several reasons the GIS tool selected for implementation of this system was GRASS.

- Natural resources applications are best suited to raster-based tools. It is primarily a raster-based tool but has limited vector capabilities.
- ANSWERS relies heavily on distributed parameter data that is represented in a manner similar to that of a raster-based GIS.
- The GRASS software is distributed as a public domain system, thus costs are reasonable, but more importantly source codes are available. The availability of source code allows other software to be more easily integrated and allows customization.
- GRASS is being used by numerous groups including the USDA SCS (Soil Conservation Service).
- Personnel at Purdue have extensive experience with the GRASS software.
- GRASS is capable of operation on a wide variety of computers ranging from UNIX workstations to 386 machines.

ANSWERS on GRASS

As described earlier, the use of ANSWERS has been limited primarily to research settings because of the time and expense required to collect its input data. Linking the model to a GIS provides access to data layers. Many of the data layers required by ANSWERS are also necessary for other GIS applications. The model could be linked to other raster based GIS tools in a similar manner, or a more modified approach could be used in linking it to a vector based tool. Other distributed parameter models could be linked using similar approaches. The ANSWERS model is described in more detail in a previous section.

Watershed Definition

Watershed boundaries were defined in one of two ways: by the program user or using the GRASS *watershed* functions. Of course one can define watersheds using traditional techniques and then develop a GIS layer showing watershed boundaries. The GRASS GIS tool contains an extensive set of *watershed* functions to assist with watershed identification (U.S. Army, 1987). Given elevation data and desired watershed sizes, these functions assist with identification of concentrated flow paths and watershed boundaries.

Extracting Cell Data

Functions were written in the C language and incorporated with GRASS to extract the cell data needed by ANSWERS (see Table 1 for data requirements). The cell data is extracted from GIS layers, formated, and placed in an ANSWERS input file. The input file is then completed by adding the remaining information that includes rainfall and channel information. The area of interest (in this case a watershed) is used to *mask* regions of data layers such that the data in these areas is not considered or extracted. This is accomplished through a *masking* procedure within GRASS.

Displaying Simulation Results

Another set of functions was written in C and incorporated with GRASS to return the simulated sediment movement results to the GIS as a new layer. This allows visualization of the erosion/sedimentation results so that problem areas can be easily identified. In addition, statistics for the layer can be readily generated and it can be used for analyses with other GIS layers.

Testing at the Indian Pine Natural Resources Field Station

The Indian Pine Natural Resources Field Station is located near Purdue University and provided an opportunity to test the spatial decision support systems described above. The Indian Pine watershed area is approximately 100 square miles in size. It consists of two major watersheds: Indian Creek and Little Pine. The upper portion of the watersheds was developed under prairie vegetation, the middle portion under transitional prairie/forest vegetation, and the lower region under forest. Currently, the Little Pine watershed is predominately agricultural with some forested areas in the lower portion. A significant portion of the Indian Creek watershed is agricultural, but the upper portion is rapidly urbanizing and the lower portion is largely forested. The Indian Pine land use patterns and changes in land use represent those in much of the Midwest U.S.

A database for the Indian Pine area has been developed in the GRASS software. A subwatershed in the northern portion of the Little Pine watershed was selected for the testing/demonstration of the ANSWERS/GRASS linkage. Watershed boundaries were determined using topographic information and using the elevation GIS data layer. The boundaries defined were nearly identical. The boundaries defined by the GIS were used for the remainder of the study. The watershed is approximately 96 hectares (237 acres) in size. The soils in the watershed are silty loams (73 hectares) and silty clay loams (23 hectares). Average slopes for the area are slightly over one percent.

The land use at the time of the rainfall event selected for simulating the watershed response was derived from a LANDSAT TM scene. The spring 1987 scene was analyzed using ERDAS software, and the classified scene was returned to the GRASS data set. Software developed at Purdue was used to export the classified scene from ERDAS for import to GRASS (Levine, 1990). The ERDAS software was used to analyze the satellite scene since the GRASS routines for image analysis have limited capabilities. The watershed land use at the time of simulation was corn (39 ha), soybeans (38 ha), and pasture (19 ha).

A 100 meter cell size was selected for ANSWERS based on the watershed characteristics. Since the GIS data were stored in 30 meter cells, they were *resampled* within GRASS to 100 meters. Data for each ANSWERS cell was extracted from the GIS and placed in an ANSWERS input file using the functions described earlier. The input file was then completed by adding the remaining input requirements by editing the file. The watershed response to the rainfall event was simulated. The simulated erosion/sedimentation data by cell was imported to the GIS using functions that were previously described. The simulated results are shown in Table 2.

Erosion (kg/ha)	Area (ha)
< 1000	35
1000 - 3000	39
3000 - 5000	17
> 5000	5

Table 2. Simulated Erosion for Test Watershed

The ANSWERS/GRASS link significantly reduced the time, expense, and expertise required to collect inputs for ANSWERS. Display of the simulated results using the GIS provided an effective means for interpretation. In addition, the results can be analyzed with other layers of information that are stored in the GIS. Additional work on the linkage between ANSWERS and GRASS continues.

Conclusions

The ANSWERS/GRASS link significantly reduces the time, expense, and expertise required to collect input data for ANSWERS. The display of simulated erosion and nutrient movement using the GIS provides an effective means for interpretation of simulation results. GIS will likely supply much of the data needed by agricultural non-point source pollution models in the future. Distributed parameter models are best suited for taking advantage of GIS technology. Traditionally, these models have been under utilized because of the time and expense required to collect the data required for operation. Agricultural non-point source pollution models that could take advantage of GIS include WEPP, AGNPS, SWRRB, ROTO, EPIC, and HYMO. GIS databases are usually developed for multiple uses, and many of these uses require some of the same data needed for modeling agricultural non-point source pollution. By adding a layer or two of information to these databases, the operation of such a model may be possible.

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INTEGRATION GIS AND CAD FOR TRANSPORTATION DATABASE DEVELOPMENT

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Abstract: A high quality and reliable transportation network is the prerequisites of a successful service route design task. Work has recently been completed on the design and development of a prototype system for creating transportation database.There are two related topics in this research:(1) analysis of data availability and adaptability to support the purpose of service route design.(2) consideration of the appropriate user environment for utilizing USGS DLG 1:100,0000 and conducting route design and analysis within the protocols presently by the Indiana Department of Transportation(InDOT). The focuses of this paper are: (1)the design and development of an interactive system for the reclassification and filtering of USGS DLG data for use in automated route design.(2) the discussions about the suitability of USGS DLG data to the route design purpose.

1.0 Introduction and Background

An important though often neglected factor in the development of strategies for delivery of public services is the design of service routes. The importance of effective route design in the public sector relates not only to the cost of service provided, but also to variety of intangible benefits such as equity and quality of service. The quality of service provided by public institutions is often very difficult to quantify. In contrast to the private sector, where engineering management objectives are usually specified in terms of economic efficiency, government agencies strive to provide the "best" level of service possible as measured by public welfare and safety. These performance criteria are generally difficult to quantify for most public service activities. An important factor, however, in the quality of services provided is the planning and management of those services. For an institution such as the Indiana Department of Transportation (InDOT), a key factor in effective planning and management is the ability to design efficient route configurations for the delivery of services. The removal of snow and ice from the intrastate highway systems is a good case in point.

In developing a strategy for winter season snow and ice removal, the goal of InDOT is to provide efficient service within the constraints on available resources; plowing and abrasive spreading equipment, sand and salt supplies, and manpower. While holding down overall cost is a primary consideration, the safety of the public is the major objective. Public safety in this context has two distinct but related components:1) the condition of the road surface, and 2) the performance of the snow removal fleet during the operation. An effective snow removal operation is one that provides rapid and orderly snow removal and abrasive application without excessive interference with public transportation activity.

Many public sector engineering management problems may be formulated and solved using network-based models (9, 10). Among the most complex problems are those that involve the routing of service vehicles for such things as trash collection, police patrol, road painting and cleaning, roadside weed control, and snow and ice control. Although a rich set of analytical methodologists evolved in an effort to solve these problems with good progresses, the data required for their applications is often enormous. For the design of snow and ice control routes on rural highways, for example, complete network distance and adjacency data are needed including precise configuration information for all major intersections. The effort required to collect, verify, and digitized these data frequently preclude their use in model development and problem solving.

The routing of vehicles for snow and ice control is perhaps the most difficult task of public sector routing problems. yet the data required for solving this problem are not significantly different than those required for other service planning and management problems. Consequently, accurate and complete representation of the physical network suitable for snow control vehicle routing will be of use to maintenance engineers for a wide range of applications such as scheduling and routing of mowing, painting, weed control, facilities and equipment servicing, inspection, and possibly some pavement maintenance activities.While ad hoc efforts to develop databases to support these models are not cost effective, not many general data collection efforts are being conducted that contain these data in digital form.

2.0 Data Consideration

For any system designed to represent geographic information, an accurate representation of the environment is essential. For most of the routing purposes, the most important data would be a representation of the state highway network. Data for the highway system could be acquired by several means such as:

- Manually entering locations of depots and intersections and distances along roads connecting these points.
- Digitizing a state road map of the study area.
- Acquiring high-resolution digital maps from third party.

Entering data by hand would allow the designer strong control over "map clutter,' as only the data for roads requiring service would be inserted into the database. However, the accuracy of these data would be questionable, as reading locations from a map cannot produce the exact locations of points. Also, for even a small study area, the data volume required to represent the network could be prohibitive.

An automatic method, such as map digitization, could reduce the effort required to process a map, but many new problems would arise. No digitization method is perfect, so much effort is required to correct the data. Also, many elements, such as divided highways, are represented by more than one line. Use of image processing techniques would be required to reduce this representation to a single line that could be manipulated by a database. Not all road maps could be scanned automatically to produce useful data; the clutter in most maps would prevent some paths from being plotted correctly. This error would result in incorrect distances between intersections, forcing routing algorithms to produce routes with incorrect costs for fuel, abrasive, man-hour, and "deadhead" miles.

The data source chosen for this research is maps in the "Digital Line Graph" form from the USGS produced from aerial and satellite photographs These maps provide high accuracy representations of roads, railroads, transmission lines, and rivers. A major advantage of using these data is the fact that they are readily available and contain almost all important information for input to the optimization algorithm described in the previous section. Work is progressing on the design and development of an appropriate user interface that will allow users to manipulate this data set directly. As the maps are available in digital form, already hand checked for accuracy by the USGS, no research time is spent in creating the maps.

2.1 Format of data

DLG data provide a vector representation of the environment. Map information is distributed by the National Cartographic Information Center of the Geological Survey in two formats: standard and optional. The primary difference in the formats is the internal measurement units used. In the standard format, all coordinates are given in pure integer values that can be mathematically transformed into geographic coordinates. A second format, the optional format, differs from the standard format in that all coordinates are recorded in Universal Transverse Mercator (UTM) coordinates. The UTM coordinate system records positions as meters east and north of a fixed point. The optional format also includes a more complete set of linkages between node, lone, and area information. The survey recommends that the optional format be used for any applications requiring transfer of data from one computer system to another (USGS, 1985).

The published DLG data files begin with a heading section identifying the geographic location of the cell, followed by one or more categories of data. The map heading includes the name, scale, creation and modification dates, and corner registration points of the map. This heading also includes edge matching information, which should indicate the extent to which adjacent maps are compatible. Each category within the DLG file begins with a record stating the category name, and the number of node, line, and area records that comprise that category.

The location information are specified by the UTM coordinates associated with each node and road segment. The topological information are specified by the relationships among node, road, and area. For example, each line will contain the information about the starting node, ending node, right area, and left area. Each node will have information about what are the lines incident to it. Each area will have the information about the lines that surround it.

The characteristics of each road segment or node are represented by the attributed code. Attribute codes are used to describe the map information represented by a node, area, or line. For example, the attribute code for an area might identify a lake or a swamp; the attributes code for a line might identify a road, railroad, stream, or shoreline; the attribute code for a node might identify the upper origin of a stream. The codes are based on the cartographic features symbolized on the USGS Topographic Map series. These maps are the basic source material used to digitize and to encode the data elements and therefore the map symbology has a strong influence on the overall classification strategy. The interesting readers are referred to USGS Digital Line Graph from 1:100,000 Scale Maps -- Data User Guide 2.

2.2 Accuracy of distributed data

The USGS does not quantify the accuracy of the produced DLG maps. Because the maps are produced from original archives maps, few allowances can be made for changes to the map area since last revision of the source data. Future goals of the National Mapping Project are to standardize all published maps and to implement a five to ten year cyclic inspection process. Most changes to the map database would be made only after the entire national database is digitized. Critical changes to the map database may be made by the Geological Survey upon special request. Alternatively, the user may modify his individual copy of the map data. The Survey does, however, state that an effort is made to insure the digitized map correctly represents the source map.

The DLG data users guide states that manually digitized source maps have a resolution of 0.001 inch, with an accuracy of no less than 0.005 inch. Automatically digitized maps are said to have a accuracy of no less then 0.0013 inch (USGS, 1985). The guide further states that the digitized data are plotted and compared to the source material to check positional accuracy and completeness of the graph. Attribute information for the map is entered manually using the original source map as a reference, and then checked by software to guarantee that only valid codes were entered. The USGS handbook does not state that this verification routine checks the entered attributes to verify that they provide a sufficient description of the line. Topological fidelity of the data is verified by software. This guarantees that no lines cross except at nodes and that any line entering a node ends at that node. Edge matching of positions and attributes in said to be performed whenever the adjacent cells are available in the database. Experimental experience with these data will show that these edge matching procedures may not be sufficient.

3.0 DLG Data and Transportation Network for Vehicle Routing

As described in previous sections, USGS DLG data are considered as the most appropriate source for the purpose of large scale vehicle routing. However, the use of this data for route design and analysis is hindered by three distinct factors. First, the DLG data set includes considerably more data than are needed for route design. For example, the county roads and the walking trails contained in DLG data set are not the concern for the routing purpose. A second problem with USGS data is that the classifications used by USGS may not be satisfactory for a given route design problem. For example, USGS does not classify intersection nodes as being inappropriate for maneuvering a snow removal vehicle through a U-turn. Third, USGS data do not provide enough direction information for routing purpose. For example, the nodes in DLG data do not present correct "cross-over" point, which will be used as a turn around point by service vehicle, on highways and the USGS DLG data fail to provide adequate and correct information about direction on highways.

In order to address these shortcomings of USGS DLG data, an interactive data filtering program has been developed to "filter" out uninteresting data and to "inject" extra information into DLG data set. This section will discuss the major concerns raised when try to apply DLG data to build a transportation network data base for routing purposes. The design and implementation details of this filter program will be provided in the next section.

3.1 Highway Classifications

InDOT uses average daily traffic (ADT) as the guidance for highway classifications. However, the classification standards of DLG data are not good for InDOT's routing purposes. For example, InDOT will treat highways in the neighborhood of a hospital as higher class roads; but, those roads will be low class roads in DLG data set. There are totally five different classes used in DLG data, but no explicit statement is available in user's manual regarding the criteria of its classification criteria. A reclassification procedure is needed to "restore" the right class of each road segment. The USGS classifications will be abandoned completely and each road segment will be re-classified by experienced InDOT personnels.

For example, the highway between node10, node9, node0, node5, node6, and node7 in Figure 1 are defined as class one road because it is an interstate highway. The highway between node4, node3, node0, node1, and node2 is a state highway, and can be classified as a class two road.

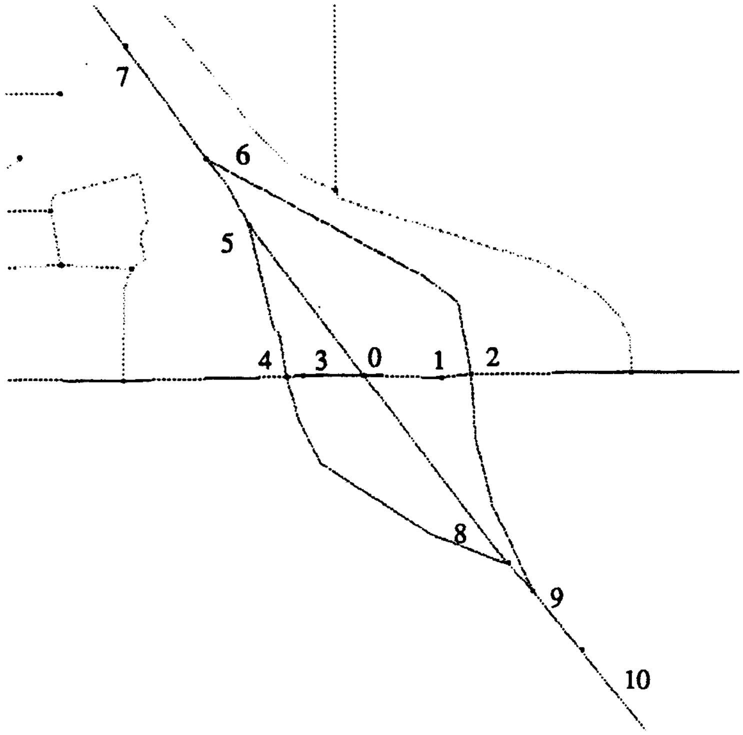

Figure 1

This figure shows the DLG presentation of a ramp area

3.2 Number of Lanes In a Road

One of the most important considerations during the snow and ice control route design procedures is the number of lanes in a road, because each lane should receive minimum services due to the requirements of InDOT policy. Although, there is a pre-defined attribute code associated with this information in DLG data set, this attribute code has not been used at all by USGS. Thus, it is essential to specify number of lanes in a road during the data base development procedures. For example, the class one road mentioned in the last paragraph is a four-lane-road; the class two road is a two-lane-road.

3.3 Direction

Direction is another very important issue in a transportation network representation. A precise and adequate representation of highway directions is essential for an effective routing algorithm. From author's standpoint, the failure to represent highway directions is the most serious drawback when try to utilize USGS DLG data for routing purpose. One-way road segments are inevitable and are very common especially in a ramp area. In Figure 1, the directions of paths node9-node2-node6 and node5-node4-node8 need to be specified explicitly during the data base development procedures because both of them are one-way roads.

In addition to the one-way roads, there are still some complicated situations existed in the ramp area. In the Figure 1, the path node7-node6-node0 are two-way highway. Based on the current configuration, it is legal to have a path like node2-node6-node5 because all of the directions are followed correctly. However, it is impossible to make such a turn in the "real world" ramp area. Suppose that a vehicle travels from node2 to node6, the next node visited is node 7 due to the physical transportation network limitations. We call this situation as "restricted direction". The following information should be stated explicitly in order to represent the ramp area shown in Figure1 more appropriately:

- node7 is the only destination, if travel from node2 to node6.
- node9 is the only destination, if travel from node4 to node8

Finally, the over/under passing intersection is another complex situation, which deserve some serious attentions. For example, node0 in Figure 1 represents an over/under passing intersection. Therefore, the path like node5-node0-node3 is not allowed, even though the current representation of this ramp area considers this path as a legal one. One way to handle this situation is to delete this over/under passing node. However, this usually implies that we will lost the planarity of the graph, which usually means that some useful routing algorithms will be ruled out. So, we will use the restricted direction method mentioned above to take care of this situation. For the ramp area shown in Figure 1, we need the following statements to specified the over/under passing situation of node0.

- node5 is the only destination, if travel from node 8 to node0.
- node3 is the only destination, if travel from node1 to node0.
- node8 is the only destination, if travel from node5 to node0.
- node1 is the only destination, if travel from node3 to node0.

3.4 Turn Around Point

Due to the limitations of truck capacity and travel distance, it is normal that a snow vehicle needs to make a U-turn somewhere on the highway and travel back to depot. There are many these "cross-over" points available for this purpose especially on interstate highways. Again, the nodes in the DLG data do not represent these cross-over points correctly and adequately because these "cross-over" points are not in the concerns of USGS during the map digitizing procedures.

In the ramp area shown in Figure1, a snow vehicle needs to travel along node2 and node6, then, make a U-turn at a cross-over point near this ramp area and travel back to node5 to continue servicing this ramp. There are two potential problems here: 1). node7 is too far from this ramp area, which will result in significant deadhead distance if this point is used as a turn-around point; 2) node7 might not be a feasible point for truck to make a U-turn. Therefore, a new node needs to be added (See Figure 1) to the appropriate place in order for truck to make a turn.

At this point, we have enough information to represent a real world ramp area as shown in Figure1. The complete statements to represent this area are:

- path node9-node2-node6 is class1 road, one-way, with one lane on it.
- path node5-node4-node8 is class1 road, one-way, with one lane on it.
- path node7-node6-node0-node8-node9-node10 is class1 road, two-ways, with two lanes on it.
- path node4-node3-node0-node1-node2 is class1 road, two-ways, with two lanes on it.
- node7 is the only destination, if travel from node2 to node6.
- node9 is the only destination, if travel from node4 to node8
- node5 is the only destination, if travel from node 8 to node0.

- node3 is the only destination, if travel from node1 to node0.
- node8 is the only destination, if travel from node5 to node0.
- node1 is the only destination, if travel from node3 to node0.

3.5 Data Redundancy

One of the major obstacles of utilizing USGS DLG data for routing purpose is because of its huge data size. There are thousands of nodes and lines in a single file. This huge data size cannot be handled by any network routing algorithm efficiently. Therefore, one of the major task for this project is to "filter out" the uninteresting data in order to reduced the amount of data which need to be handled. Figure2a and Figure2b show the raw DLG data and filtered DLG data of Lafayette area, Indiana, respectively.

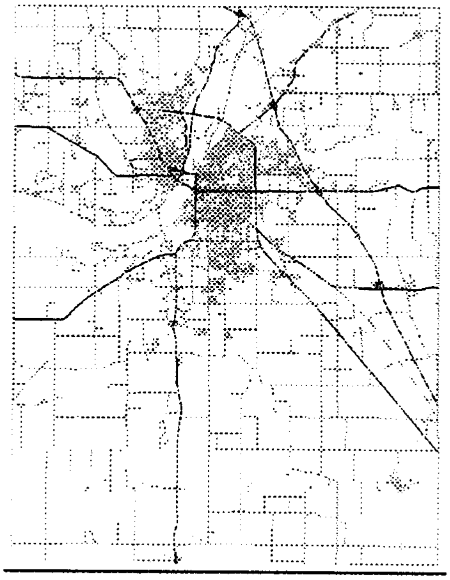

Figure2a Original DLG Data

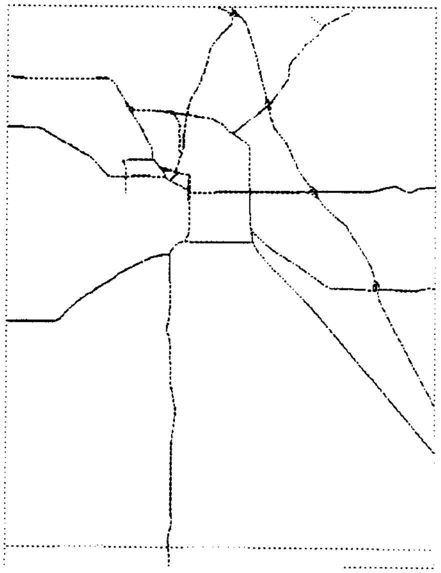

Figure2b Filtered DLG Data

4.0 Interactive Data Filter Program

The structure and function of this interactive DLG data filter described in this paper is represented in Figure3. It consists of three sperate functions: 1) input of the original DLG data file(s). 2) interactive reclassification of road segment and node (intersection) objects and 3) output of reclassified data files in DLG format. Each of these phases is discussed briefly, below.

4.1 Data Input

The original USGS DLG file(s) will used as the input of the data filter program. There are two steps need to be considered during this stage.

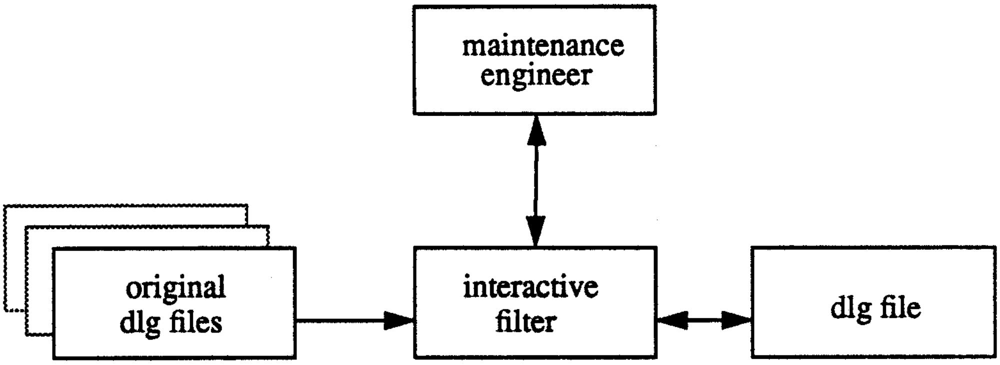

Figure3: Schematic of the data filtering process

4.1.1 Maps Selection

USGS divided each thirty-minute area into four or sixteen separated files and refers each file a name. This data filter program will user a user friendly environment and allow user to select as many files as (s)he wants. A representation of such a window is shown in Figure4.

4.1.2 Neat Line and Maps Merge

Some boundary lines (called neat lines) were used by USGS to locate the edge nodes and to maintain the topology continuity in each DLG files. It is necessary to merge the selected files into a single one due to the convenience of the implementation. Therefore, some of the neat lines are redundant and need to be removed. Figure5 shows the idea of the neat lines removal and map merge. Notice that some of the neat lines still need to be kept for the future possible merge.

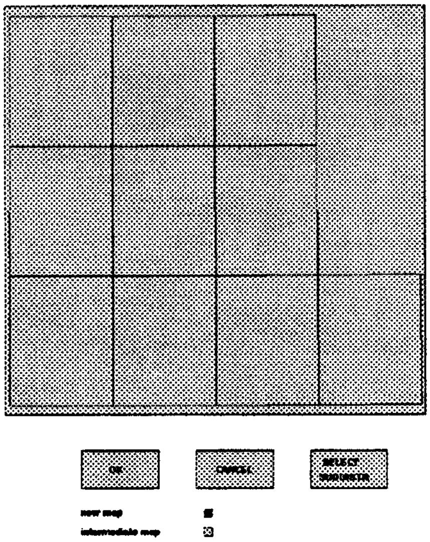

Figure 4

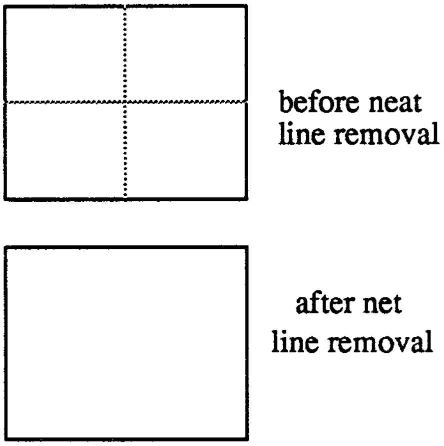

Figure 5

4.2 General Structure of Data Filter Program

Figure6 shows the major components of this data filter program. Road classification component is used to specify the characteristics of roads, and node classification is for the node specifications. Utilities component contain several useful tools to help user to conduct the filtering task easier. Each of these components will be discussed later.

4.3 Network Object Classification

The ultimate goal of this data filter program is to produce a suitable data set that can represent the network properly. Thus, road and node specification play the two major roles in this data filter program. An interactive method is presented for the purpose of road and node specifications.

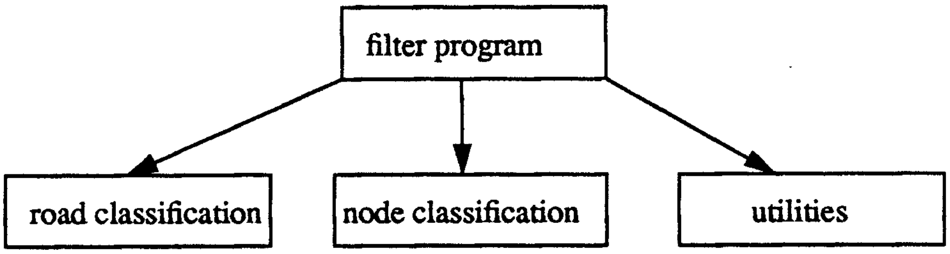

Figure 6

In this application six major road classifications are required: class1, 2, and 3 based on ADT data, direction restrictions, roads that do not require service, and all other (uninteresting) roads. Separate functions are provided for each group of classifications. Figure7 shows the basic logic of roadway classification.

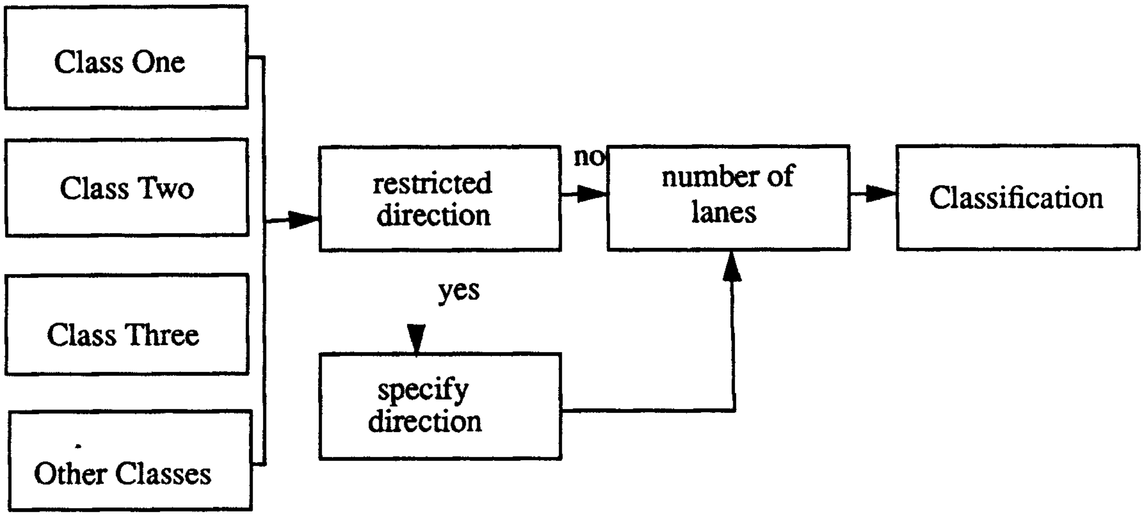

Figure7: Schematic representation of road specification procedures

Also, there are several functions for the node classification purpose, which include: unit node (depot location), no U-Turn allowed, add new node, and uninteresting. The basic logic of node classification can be presented by Figure8.

In addition to the basic road and node classifications, this data filter also provides several convenient functions to help user conduct the filtering task. The following table shows the capabilities of these functions:

TABLE 1. Utilities Functions

Function Name	Capabilities
zoom	zoom in or zoom out of a certain area.
highlight	highlight a certain road
information	show information of a certain road
showme	show the current status of classification
panning	panning windows
check direction	verify restricted directions

5.0 Implementation

According to the above descriptions, it is obvious that human (route experts) experiences and knowledge about transportation network are very important during the data filtering processes. The field engineers from each highway district have been identified as the most appropriate persons to conduct this data filtering task because they are the persons who have enough knowledge about the physical transportation network and the routing policies.

This data filter program has been completed under the assistance of InDOT. The field engineers from Crawsfordsville (Indiana) had finished using this data filter program to "reclassify" the data that cover their responsible areas. The preliminary results and the feedbacks from this early implementation is exciting and courage. The total working days to conduct the entire Crawsfordsville district needs about 8 9-hour working days. When this high quality transportation network GIS data base is built completely, it is expected to serve for multiple purposes, such as snow removal, highway maintenance, weed control, and emergence services.

Reference

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2. Minsk, D.L, "A systems study of snow removal," *Transportation Research Board Special Report No. 185*, 1979, 220-225.
3. Public Service Office, "The Indiana Department of Highways 1985-86 Snow Packer," InDOT Publication, December, 1985.
4. U.S. Geological Survey, *Digital Line Graphs from 1:100,000 Scale Maps, Data Users Guide 2*, Reston, VA, 1985.

A Description of LANDSIM and Its Uses

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INTRODUCTION

Amid the increasing attention the environment is now receiving, it is noteworthy that geographic information systems can provide practical tools to minimize environmental damage caused by essential human activities. A significant example of such activity is the ongoing training the U.S. Army must conduct. Decreasing budgetary resources combined with increasing training requirements and expanding environmental concerns make it difficult to train efficiently while maintaining training land condition. Although several models exist for optimizing land use, land planners have lacked both an efficient means to automate the models and a mechanism to integrate the models with scheduling systems already in place. To resolve this situation, Coe-Truman Technologies, Inc. developed LANDSIM, the Training Land Impact Models Simulator. LANDSIM provides land use planners with a powerful, easy to use GIS tool to run these training land impact models, estimate rehabilitation requirements, and compare the results of rehabilitation against different land impact models.

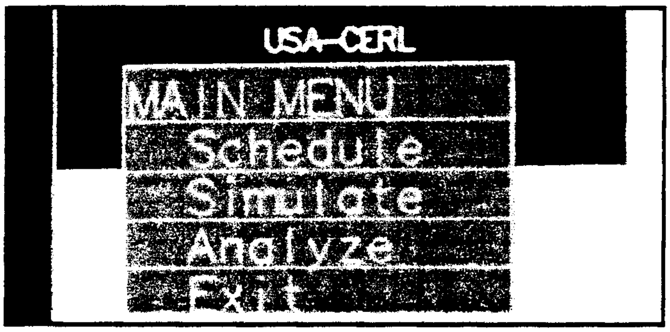
LANDSIM was developed for the Environmental and Natural Resources Division of DEH, Fort Lewis, and the U.S. Army Construction Engineering Research Laboratory (USA-CERL), and is currently used for modeling potential uses of Army training lands. However, CTT designed LANDSIM as a generic simulation tool that can run specific models for a variety of applications. With the appropriate data and classification schemes, LANDSIM can benefit any land planner by illustrating the geographic impact of various land use options. From these options, the planner can choose the one that provides the greatest utility with minimum cost and environmental damage.

GRASS

The geographic information system CTT chose for LANDSIM is GRASS, (Geographic Resource Analysis Support System). Designed and developed by USA-CERL, GRASS is a grid cell (raster) based tool. In a raster format, the landscape is divided like a checkerboard into regular rectangular parcels of land. Attached to each parcel are identifying characteristics such as land cover, land use, vegetation, geology, slope, elevation, soil type, political boundaries, and human structures (e.g. streets and buildings), among other features. GRASS was chosen for its flexibility, public domain status, widespread use by the Army, and its broad support base.

User Interface

One of the key requirements of LANDSIM development was its anticipated use by novice computer and GIS users. An intuitive user interface, employing pull-down and pop-up menus, dramatically reduces the time users must spend learning the mechanics of operating the program, leaving them with more time to concentrate on the actual simulation. GRASS lends itself to this design by making menus possible and relatively easy to program. The user simply selects an option from the menu with the mouse. The menus spare the user from having to learn several arcane commands to navigate through the program.

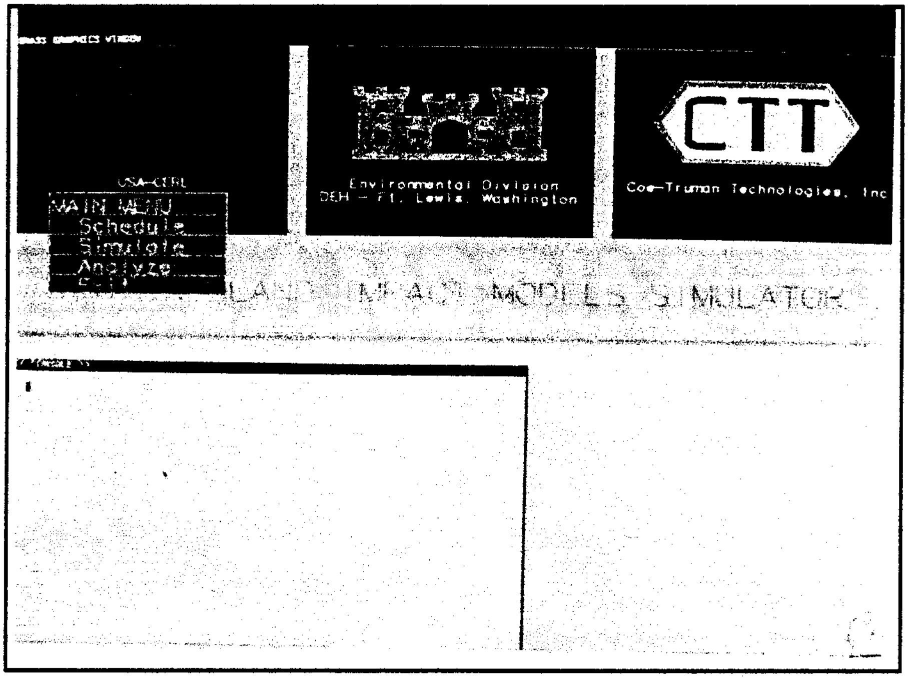


Furthermore, the LANDSIM menus have been logically arranged to reinforce the steps one must take to set up and run a simulation properly. The first set of menus explain the different types of events that impact the training land. The next set of menus offer a selection of models to use in the simulation. The third set of menus allows the user to analyze the simulation data and create three-dimensional displays of each map layer.

LANDSIM Operation

To run LANDSIM, the user simply double-clicks on an icon and then sees the LANDSIM opening screen, with its accompanying Main Menu. In the lower left corner of the screen, a

Console window will appear for the user to specify the training areas to be displayed by LANDSIM.



The Main Menu and the Console window are used for all data entry in LANDSIM. GRASS output will appear in one or all of the three windows contained within the LANDSIM window, while LANDSIM report output will appear in the Console window. Before the user runs a simulation, the three LANDSIM windows each contain a logo representing the organizations responsible for the LANDSIM DEMO: the Environmental and Natural Resources Division of DEH Ft. Lewis, USA-CERL, and C.T. Technologies.

The user first selects the Schedule option, which presents the Schedule Menu. This menu allows the user to specify which events to include in the simulations. Because LANDSIM has been developed for Army training lands, the current version allows the user to access training schedules from the Range Facility Management Support System (RFMSS) and the Standard Army Training System (SATS). The events scheduled in these systems can be directly loaded into LANDSIM, thereby saving the user the work of manually entering the training exercise information. Other event types are as follows:

- additional training exercises
- land rehabilitation measures (Disking; Disking/Seeding; Disking/Seeding/Fertilizing; Disking/Seeding/Fertilizing/Irrigation; Grazing; Seeding)

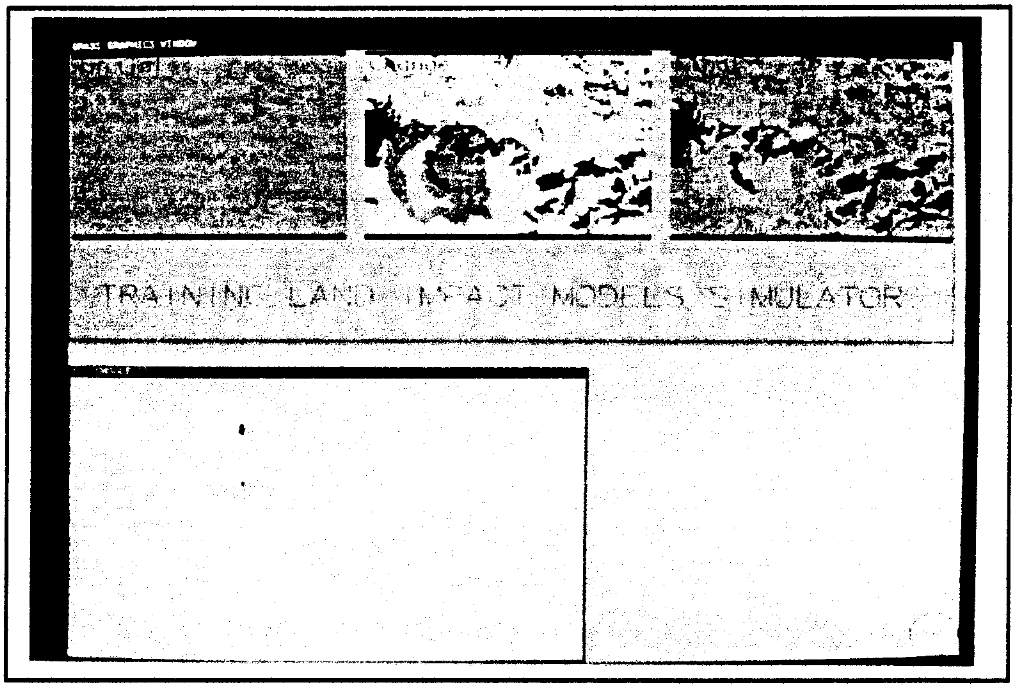
- agricultural activities (outleases, grazing, fire, and endangered species)
- forestry activities (planting, harvesting, insect infestation and treatment, and endangered species)
- environmental conditions and events (universal soil loss equation, slope, soils, activities, and training events).

After specifying the schedule events, the user returns to the Main Menu and then selects the Simulate option. The resulting Simulate menu allows the user to choose a model to be used during the simulation and to specify model parameters. LANDSIM will run the following training land simulation models: Change Detection, TADCAP, TVD, WES, and the LANDSIM demo. LANDSIM's modular design permits additional models to be added as they are developed, or a completely different set of models to be included for a different application.

Once the user has chosen a simulation model, the simulation begins. The left window will display a map representing the initial state of the land. The right window will display the state of the land as it is impacted by events. A special feature of LANDSIM makes this an active window; that is, it continuously updates to show how changes occur over time. The user can specify how often LANDSIM updates this window. For instance, if the user wishes to see the impact of events over a 60 week period, he or she can tell LANDSIM to update the right window at a rate of every week, every five weeks, every ten weeks, or only display the final result, all in a matter of a few minutes. Not only does this flexibility allow the user to set the simulation at a specific pace, but it also encourages the user to learn more about the events being simulated by seeing how gradually or immediately events impact the land.

The center window will display the difference between the initial state and the final state, once a simulation has been completed. Thus, when the simulation has completed its course, the user can view at the same time the initial state of the land, the state of the land after events have occurred, and the degree of change between the initial and final states.

An illustration of LANDSIM as it appears after a completed illustration can be found on the next page.



To run the model simulations, LANDSIM uses factors for stress, soil type, vegetation cover, event types, and any other geographic features required by the model. For example, each of the following calculation factors is included for each event taking place in a LANDSIM simulation for an Army training land:

- soil type
- slope
- vegetation cover
- unit type
- event type
- week of year

If, for some reason, the soil type, slope, or vegetation cover data is missing for an area, LANDSIM automatically shades this area black to indicate that the data is not available and that the impacts cannot be calculated.

Each event has a different impact, depending on the calculation factors. For example, a training event run in Spearhead, SD in December and January (week 51 through week 4) will have no effect on the vegetation cover in the simulation because the models assume that several inches of snow are covering frozen ground and that units will not be driving over trees. However, the same Bivouac, FTX, or CPX held during February, March, April, or October has a tremendous impact on the land. LANDSIM will show a greater impact because the simulation models assume a high level of soil saturation during these months based on historical weather patterns and gathered observable criteria from that area.

The weather also affects rehabilitation events. For instance, planting seed in July accomplishes little because not enough soil moisture exists to sustain germination or growth. On the other hand, planting during the growing season results in an increase in vegetation cover. To accurately simulate the effect of rehabilitation events, LANDSIM factors these and other climatic influences, such as the benefit of irrigating in addition to planting, and the negligible effect of planting in December and January. Thus, by incorporating weather and seasonal variables, LANDSIM can produce accurate, realistic simulations.

To calculate growth, LANDSIM considers both erosion and plant growth data. The extent of erosion is based on the soil type, slope, and vegetation cover. For instance, a sandy, steeply sloped area with no vegetation cover will deteriorate, whereas loam on a flat area may experience growth, even if it originated as bare soil.

Thus, LANDSIM's modeling procedures and simulation algorithms take into account not only impact events, but also the environmental factors that determine the extent to which events affect the training land. These factors enable the LANDSIM DEMO to produce realistic, credible simulations.

After running a simulation, the user can perform any of three options:

- Return to the Schedule Menu to modify the events;
- Return to the Simulate Menu to run a different model on the same events;
- Go to the Analyze Menu to further study the current simulation.

The Analyze Menu allows the user to produce reports based on the simulation. These include for the current version of LANDSIM: classification data, Standards in Weapons Training (SIWT) requirements, land rehabilitation budget, the 3-D displays, and map layer information. Of course, the reports can be tailored for any land management application. The reports available for the Army training land version of LANDSIM provide a good indication of the information available, and are detailed below.

Classification

The classification option will print a complete Map Layer Category Report. This report details the degree of change in vegetation between the initial and final states of an area. Using a scale from 1 to 100 (1 represents extreme vegetation loss, 100 represents major vegetation gain) the report indicates the number of map cells changed for each category and translates that number to the percentage of the land affected. The report will also convert the percentages to acres, hectares, and square kilometers.

SIWT requirements

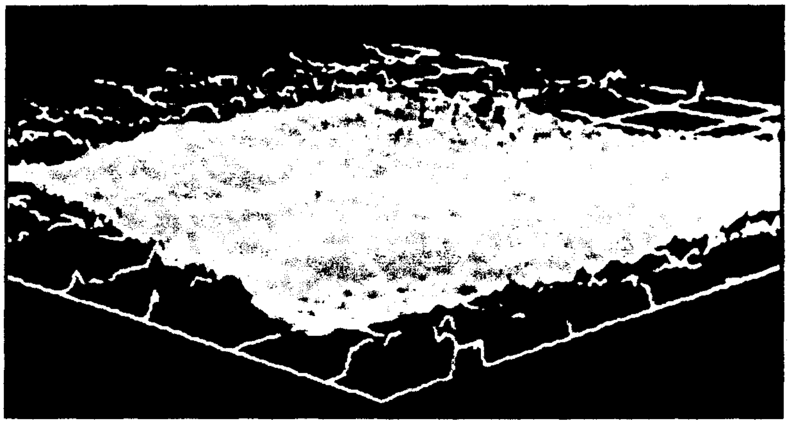
When implemented, this option will produce an SIWT requirements report. This report will show to what extent the unit has met its SIWT requirements based on its projected training activities, as well as activities to date, in accordance with the SIWT regulation, AR 350-38. This function is especially useful because with LANDSIM planners and trainers can easily determine how the changes to a unit's training schedule will affect its SIWT status.

Rehab Budget

When implemented, this option will produce a Rehabilitation Budget report. With both text and graphics, this report will represent the relative costs of rehabilitation for training facility areas. Planners can use this information to forecast the rehabilitation budget and prioritize rehabilitation events. Moreover, this option will give planners the power to compare the costs and effectiveness of different rehabilitation plans based on the time of year. Because LANDSIM automatically calculates erosion data, planners can use the program to determine how much more expensive a rehabilitation plan will be if delayed a year or more.

3-D Display

This option produces a three dimensional display of any map layer in the center LANDSIM window. Users can manipulate the vertical exaggeration, field of view, number and extent of grid lines, map resolution, and elevation. The illustration on the next page represents a 3-D display for data from the Spearfish, SD map sheet and data base.



Layer Info

The Layer Info option provides in a report the complete map layer information for any map layer file in the system. This information includes:

- file name
- location
- mapset
- title
- date of report
- login of creator
- type of map
- number of
    - categories
    - rows
    - cells
- projection data
    - north
    - south
    - east
    - west
    - N/S resolution
    - E/W resolution
- data source
- data description.

Hardware Platforms

LANDSIM can run on a variety of platforms; however, the most efficient is currently the IBM RISC System/6000. The machine's speed permits a lengthy simulation period to be displayed in a reasonable amount of time while still pacing the simulation to show incremental changes in the land cover. For example, there is almost a four minute difference when running LANDSIM on the IBM RISC System/6000 versus the Sun 3110 when simulating a 104 week period scenario. A user can sit at the workstation and watch screen changes which appear almost as a moving picture due to the System/6000's speed. The speed permits a greater degree of realism in the simulations.

Conclusions

LANDSIM has many benefits beyond providing its users with a tool to select among options for land management. As stated earlier, the hierarchical menu system contributes to the user's understanding of how to create and analyze a simulation. Because the user must carefully establish events prior to the simulation, he or she will gain a better understanding of how events work upon existing conditions to change a landscape. Then, by having an easy means to run different simulation models on the same set of events and conditions, the user learns that a simulation is only as good as the model behind it, and can develop a sense of the strengths and weaknesses of each model. The tools provided by the Analysis Menu give the user additional ways of looking at the geographic data, and reinforce the principle that geographic information systems require interpretation and analysis beyond the map displays. Finally, as a simulation program, LANDSIM encourages its users to learn more about the process they are simulating. Users are much more likely to reexamine their plans and develop alternatives when an easy method exists to model and analyze the various options.

LANDSIM brings to land planners the ability to ask "what if" as often as desired for a variety of situations. With an easy to use menu-driven interface, a variety of simulation models, a thorough consideration of climatic and environmental variables, and the ability to display impacts as they occur, LANDSIM will enable its users to manage land efficiently while they learn more about efficient land management in the process.

B-infer: A Bayesian Reasoning Shell for Spatial Decision Support

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Abstract. A spatial decision support system (SDSS) is presented that demonstrates the integration of a probabilistic inferencing procedure based on Bayesian analysis, with a geographical information system (GIS). The system was developed to aid land planners and managers in the determination of suitability indices for specific land use activities. To provide a context for understanding the use of this SDSS applications generator, an overview of SDSS in general, and the role of non-procedural and probabilistic reasoning in land suitability analysis is presented, followed by a detailed description of a Bayesian spatial reasoning shell known as B-infer.

1 Introduction

The premise behind the use of formal of land use allocation models is that certain geographical regions are better suited for specific facilities and land uses than other geographical regions. The goal of land allocation models is to generate good strategies for the assignment of specific land use activities to the most suitable available land units, based on appropriate measures of suitability. As distinguished from the widely-studied facility location models that treat optimal locations as points in a plane or along a network, land use allocation models treat optimal locations as two-dimensional areas.

Consider the region of interest to be partitioned into an arrangement of N non-overlapping geographical units numbered from $i = 1,2,...,N$. Every basic geographical unit can be characterized by a set of economic, environmental, and spatial attributes. Full and complete knowledge about the attributes for each unit is assumed. A subregion is any contiguous grouping of these units. The economic, environmental, and spatial characteristics of any subregion are a function of the collective attributes of the units comprising that subregion. Thus, for example, the total area of a subregion allocated for a land use is the sum of the individual areas of the units comprising that subregion.

The cost of acquiring and developing unit i for a specific land use can be based on a number of market and non-market factors, including physical characteristics of the land, proximity to services, etc. The suitability of a geographical unit, s_i, is defined to be a "measure of the physical capacity of a specific location (i.e. geographical unit) to support a specific land use" (Anderson, 1987). This determination is usually based upon natural characteristics of the land such as slope, soil type, and other physical factors. A number of mathematical models have been proposed to calculate suitability ratings as functions of these factors and underlying natural processes. The output from these models is a map of information depicting the relative capability of any given geographical unit to support a given land use. These models are discussed at length in Hopkins (1977), Chapin and Kaiser (1979), Anderson (1987), and Diamond (1988).

The underlying assumption of this discussion is that the problem of selecting or allocating a particular set of geographical units as a subregion for a particular land use is appropriately partitioned into three sub-problems (see Diamond and Wright, 1988): 1) collecting, storing and managing data to be used in the determination of suitability for the intended land use, 2) the evaluation and analysis of data about each geographical unit to make that determination of suitability, and 3) the development of a strategy for selecting the set of units to form the subregion. Furthermore, three traditionally disparate technologies are most appropriate to address these sub-problems: 1) spatial data management using geographical information systems (GIS), 2) expert systems (ES) for determining land suitability, and 3) numerical optimization for identifying dominant land allocation strategies. The focus of this research is the design and implementation of a shell development environment that can be used in the determination of suitability indices for a given land use allocation activity. Implementation results in a "tight coupling" of modern GIS technology (a popular raster-based GIS) and a Bayesian inferencing procedure for purposes of generating GIS maps displaying the probability of land impacts for a given allocation strategy. As a shell environment, this system can be used to develop application-specific spatial decision support systems (SDSS) when a Bayesian predictive model is an appropriate probabilistic inferencing mechanism.

Very recently, the deficiencies of modern GIS technologies to support more than only very simple data analysis and modeling activities have received considerable attention. Most notably, Densham and Goodchild (1989) offered the following position statement to participants at the specialists meeting for the 6th Initiative of the National Center for Geographical Information Analysis held in Santa Barbara in March, 1990:

> "Definitions of geographic information systems often focus on the capture, storage, manipulation, analysis and display of spatial data—implying that geographic information systems implicitly are designed to support spatial decision-making. For many spatial problems, however, geographic information systems do not support decision-making effectively: analytical modelling capabilities are lacking and system designs are not flexible enough to accommodate variations in either the context or the process of spatial decision-making. One response to these needs is the development of spatial decision support systems. We draw a distinction between geographic information systems and spatial decision support systems in terms of system design, the types of problem to which each can be applied, and the decision-making process supported."

To provide a context for the development of a spatial reasoning shell, we begin with a discussion of the emerging technology of spatial decision support systems followed by a rationale for non-procedural and approximate reasoning applied to the determination of land suitability indices. We then present an overview of the B-infer SDSS, and conclude with a discussion pointing out future research directions.

2 Spatial decision support systems

Decision support systems (DSS) evolved in the late 1960s and matured through the 1970s in response to the needs of the business data-processing community for more complete modeling capabilities, as well as better interaction with these models than that offered by management information systems (MIS). A DSS is a system providing support for decision-makers in semi-structured or unstructured situations by bringing together human judgement and computerized information (Turban, 1988). If there is weak agreement as to a definition of DSS, there seems to be a general consensus that, at least conceptually, DSS are comprised of three components as described schematically in Figure 1:

> A data management subsystem that includes data query and management routines and necessary internal information about data structures.
>
> A models management subsystem that includes an appropriate suite of systems models, a directory of models and their requirements, and utilities for integrating and executing model elements.
>
> A dialog subsystem consisting of the hardware and software that provides the interface between the user of the system and the system itself.

A rich collection of software tools is available for the development of these individual components, but only recently have efforts focused on general purpose DSS development environments. Indeed, the technologies supporting the development of data management subsystems and dialog subsystems are quite mature, while the technology for model-based management systems is still relatively young. However, recent major advances in object oriented programming systems (OOPS), hierarchical data structures, and compiler construction environments should speed the development of powerful model-based management systems.

When a DSS is developed for use with a domain database that has a spatial dimension (one or more data attributes having a distribution over space), or when the solution space generated by the DSS has a spatial dimension, the analytical system in aggregate may be referred to as a spatial decision support system (SDSS).

As suggested by Densham and Goodchild (1989), this description effectively describes spatial decision support systems (SDSS), and also serves to distinguish SDSS from geographic information systems (GIS) suggesting that some GIS functionality is an important component of any meaningful SDSS. From another perspective, the difference between GIS and SDSS is that SDSS deals with a solution space provided by one or more analytical (modeling) elements, as well as a problem (geographical) space manipulated by the GIS database. Thus GIS is an important component of any SDSS.

The integration of GIS and DSS technology toward the development of SDSS applications would appear to be particularly useful in addressing problems requiring effective land suitability analysis. The determination of land suitability has been an important problem for a variety of planning activities. Examples of these activities include land use planning, site planning, facility location, corridor selection, and impact assessment. In all of the above examples, the suitability of a land area to a specif-

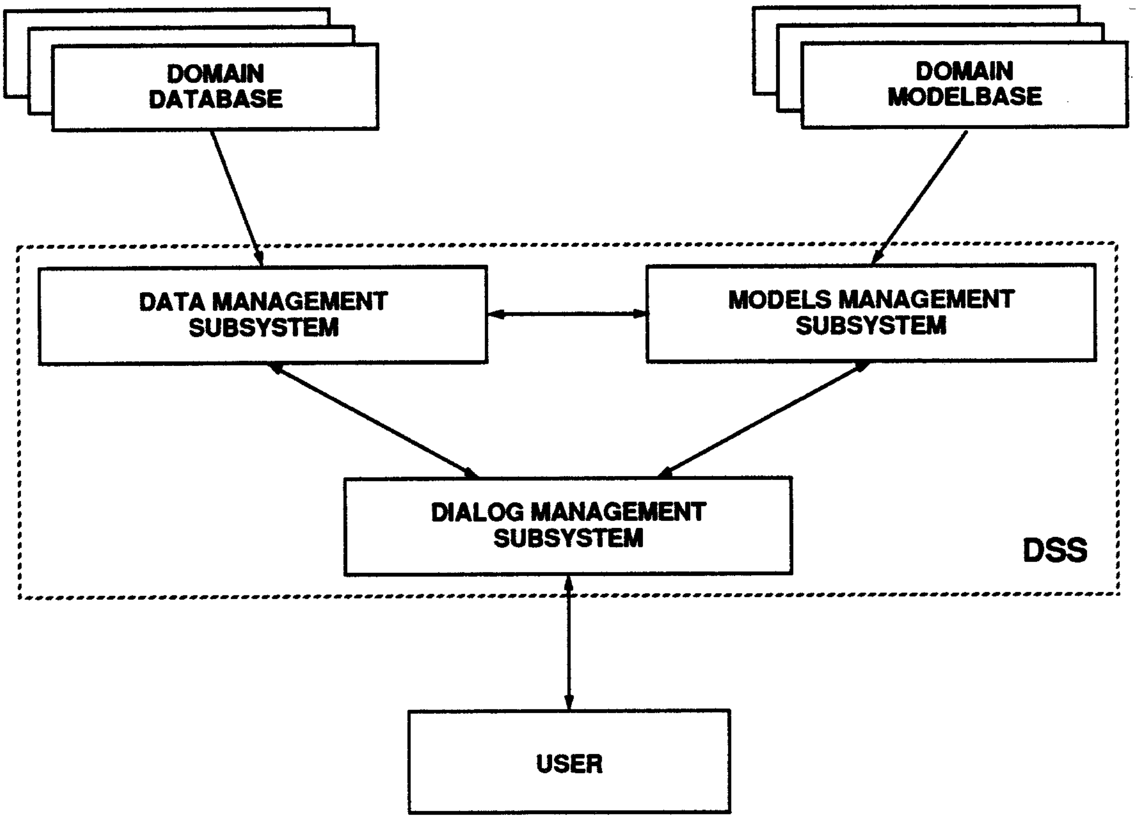

Figure 1 Logical framework for DSS applications showing the relationship between the three principal DSS subsystems; a data management subsystem, a models management subsystem, and a dialog management subsystem. A given implementation may actually integrate all these elements into a single program module depending on the DSS generation technology employed.

ic purpose or activity is must be determined in order to make a good decision about the allocation of an activity. For the purposes of this paper, the term land suitability should be viewed as the relative ability or inability of a land area to provide the characteristics (factors) needed to support an activity or land use given the factors deemed important to the activity.

Methods of land suitability determination are based largely on identification of the factors that contribute to the suitability of the land for the purpose at hand, and the subsequent combination of these factors to produce some sort of suitability map. Hopkins (1977) provides a taxonomy of several methodologies for the generation of land suitability maps. Lyle and Stutz (1983) provides an excellent discussion of the computerization of this suitability map generation.

Since the late 1960s, GIS technology has been used to generate suitability maps. Earlier techniques were insufficient in that they did not allow for different weights on the factors affecting suitability and/or they ignored location of activities based on factors other than those of an ecological nature. Overcoming these limitations seemed to require the use of computerized systems. Many case studies exist that have taken advantage of GIS in the determination of suitability for later use in planning studies (Antenucci and Dangermond,1974, Dangermond 1974, Williams, 1985). In all cases the conclusion seems to be that GIS technology is extremely useful in aiding all types of regional and land planning activities.

The application of expert systems and proximate reasoning technologies to the analysis of land suitability is a relatively new concept. An even more recent concept is the idea of integrating expert systems with some database of geographic infor-

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mation (whether the database in question is a true GIS or not). The role of AI (and especially expert systems) in solving spatial problems, however, has been well documented. Davis and Clark (1989) have provided an excellent bibliography of expert systems in natural resource management. The preceding discussion of SDSS, its potential use in conducting land suitability assessment, and tools for efficient applications development, provide a framework for understanding how techniques for suitability analysis based on established analytical procedures may be integrated with GIS technology. In the following section, we provide a more detailed description of this type of integration.

3 Non-procedural and approximate spatial reasoning for suitability analysis

Most land use suitability assessment models are based on manipulations involving "factor maps." A factor is a unique geographical attribute such as slope of terrain, soil, or vegetative cover. Variations within a factor such as degrees of slope or soil classes are referred to as factor *types*. A factor map is a map showing the geographical location and distribution of factor types for a given factor, and can be combined in various ways to generate a composite map depicting, either graphically or numerically, the relative capability of any given geographical unit to support a specific land use. A variety of different strategies for achieving these combinations have been suggested:

1. *Linear combination* is a common factor combination technique. This method relies upon the decision maker to supply both a rating schedule and a weighting schedule. The rating schedule depicts the relative suitability of the various types within a factor. For example, slopes greater than 20% are rated 0, between 10% and 20% a 5, and less than 10% a 10. The weighting schedule depicts the relative importance of the various factors in determining the suitability of a unit. For example, slope might be twice as important as depth to bedrock. The ratings for each type are multiplied by a weight for each factor and the result is summed.
2. The composite score for a unit might be conditioned upon the presence or absence of a factor or interactions between factors. If these interactions are well-defined, then it may be possible to define a nonlinear function that explicitly captures these relationships. For example, a soil loss rating can be easily computed from standard equations given information on land cover, slope and watershed shape. As such, *nonlinear combination* methods can be very useful when applied to specific components of an overall suitability assessment. However, in practice the relationships between factors are rarely well-understood and it is difficult to represent most interactions as mathematical functions (Anderson, 1987).
3. The *direct assignment* technique involves enumerating all possible combinations of factors, and assigning a composite score to each unique combination when all factors are considered simultaneously. The advantage of this method is that it requires the explicit consideration of interactions between factors. The disadvantage of this method is that the number of composite score assignments that must be made increases exponentially with the addition of new factors.
4. The *rules of combination* method involves the use of explicit rules to assign suitabilities to *sets* of types rather than to single combinations. Rules of combination are expressed in terms of verbal logic rather than in terms of numbers and arithmetic. For example, "if type 1 of factor X and type 2 of factor Y occur together in a region, then the rating of factor X type 1 overrides that of factor Y type 2." These rules are based upon an understanding of the underlying natural system being described rather than on a single set of relationships repeated for all combinations regardless of the specific types and factors being combined. If properly devised, rules of combination can handle interdependence between factors. Furthermore, they do not require an explicit mathematical relationship as do nonlinear combination methods.

The integration or rule-based expert system technology and GIS, provide an excellent framework for automating suitability assessment via rules of combination methods. Suppose that an activity is to be assigned to a region and the suitability for any particular cell to support that activity has been judged to depend on slope, geology and forest density. Suppose further that complete categorical information for the region of interest exists in a GIS as discussed above. An example of a combinational rule that might be used to determine suitability might be:

```
IFMAP slope 1-3
ANDIFMAP geology 4-6
ANDNOTMAP density 4
THENMAPHYP 4 suitability
```

This rule contains the judgement that if, for any particular cell, the average slope falls into slope categories 1, 2 or 3, and the average geology is of type 4, 5 or 6, and the forest density is not of type 4, then a suitability of 4 may be assigned.

For many problems requiring the determination of land suitability, applications are so diverse and unique that available knowledge is too incomplete or inexact for the use of formal rules of combination. Indeed, a domain expert may not be available or may not be able to articulate a rule set to a sufficient degree of precision. For these applications, a probabilistic inferencing procedure may be acceptable.

An "ideal" land allocation procedure using probabilistic reasoning to perform land suitability might be structured as shown in Figure 2. Such a 2-level process might employ a formal procedure for computing the probability of an impact level that might be expected to result from the probabilities of various determining factors; level 1. Suitability would thus be determined in terms of the probability of experiencing one of a finite number of impact levels for a well-specified activity. An optimal allocation strategy, as measured by one or more sets of evaluative criteria (objectives), would be generated using some formal optimization procedure based on these probabilities; level 2. Instead of determining suitability based on a set of rules reflecting the subjective judgement of a domain expert, suitability in this instance is determined based on historical observations in the form of prior categorical probabilities for various impact levels.

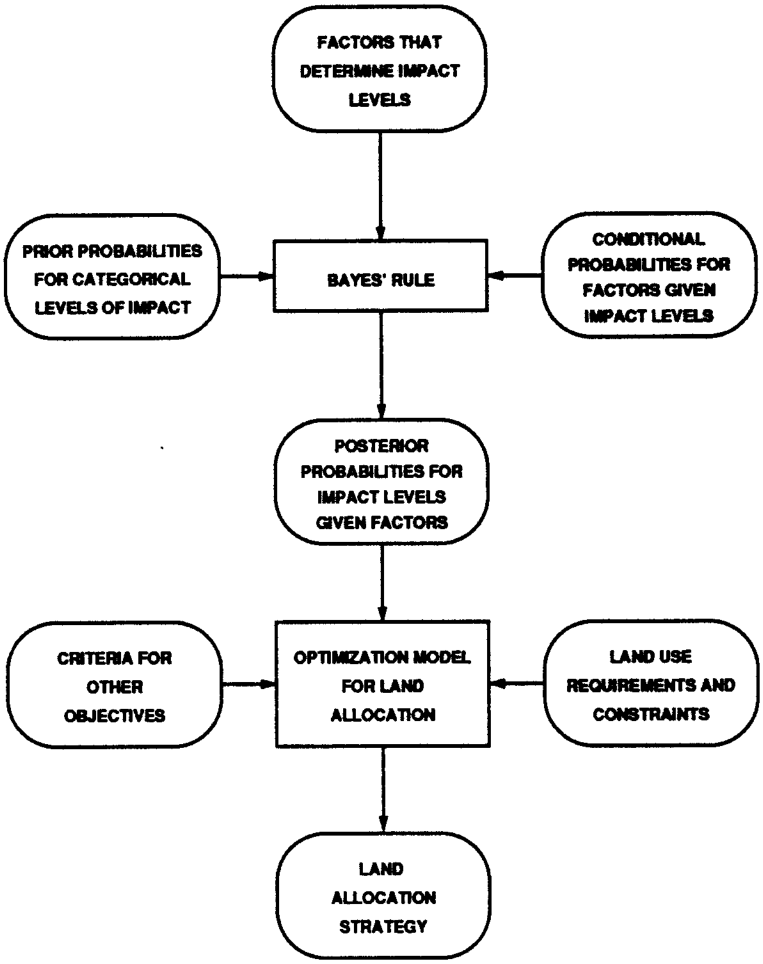

Figure 2 An idealized system for land allocation in which suitability assessment is accomplished by Bayesian analysis using a database of prior categorical probabilities, an input of determinant impact factors, and a set of conditional probabilities for factors given specified impact levels. The resulting posterior probabilities for impact levels are become suitability indices that are subsequently used by a formal optimization procedure in the assignment of land units to activities.

One such procedure for determining these impact probabilities is the use of Bayes' Rule. Define H_i to be the i^{th} member of the set of all possible outcomes of an event H, and E_j to be the j^{th} subset of events in the set of possible events E that result in an outcome within H. Bayes' theorem may be used to compute the probability that the outcome H_i occurs given that the set of events E_j has occurred (Miller and Freund, 1985). In this case,

$$P(H_i|E_j) = \frac{P(E_j|H_i)P(H_i)}{\sum_i P(E_j|H_i)P(H_i)} \qquad (1)$$

Assume that a set of appropriate factors can be identified that influence the suitability of a land area for a particular land use. Each possible combination of values of these factors make up the subsets E_j, and the set of all E_j's make up the set E. Furthermore, assume that an accounting could be made of these factors over many occurrences of this particular land use. Finally, assume that the suitability is judged (by a domain expert) to fit into one of a finite number *(n)* of appropriate categories of suitability, $H = \{H_1, H_2, ..., H_n\}$, and that an accounting of factors was made relative to this predefined set. This accounting would then represent a database of categorical past experience about that land use action, which could then be used in conjunction with Equation 1 to predict the probabilities of each member of H occurring for land areas designated for the same activity, provided that the values of the contributing factors, E, are known.

For purposes of this research, there are two assumptions inherent in this approach. First, the set of factors, E, are assumed to be mutually independent (exclusive). Independence means that any subset of the evidence must not affect the value of the rest of the evidence; a restriction that may prove troublesome because a comprehensive analysis of correlation should be done to guarantee independence (Gillette, 1989). Second it is assumed that the set of evidence, E, completely (exhaustively) covers the set of possibilities that effect the set of outcomes, H. This requires that a study of the factors that contribute (or do not contribute) to suitability be made, and that an all inclusive set of factors be monitored over time to facilitate satisfaction of the first assumption. The validity of the Bayesian model for a given application requires satisfaction of these assumptions.

An essential input to the probabilistic inferencing procedure discussed above is an historical profile of past impact resulting from previous instances of the activity of interest. To demonstrate how probabilistic reasoning as described by this example may be incorporated into a spatial decision support system, an SDSS application generator was developed for use in determining profiles for probable impact resulting from the assignment of military training activities to specific land areas (Buehler, 1990). The system is called B-infer—for Bayesian inferencing—and has been implemented as part of a well-known raster-based GIS; the Geographical Resources Analysis Support System (GRASS) developed by the U.S. Corps of Engineers (Westervelt, 1988). The following section of this paper presents an overview of B-infer. A more complete description of the system and its implementation may be found in Buehler and Wright, 1990a, 1990b.

4 A Bayesian reasoning tool

The approximate reasoning procedure using Bayesian analysis as discussed in the previous section has been formalized as a shell development environment that allows a land management domain expert to develop a spatial decision support system for determining land suitability profiles. The system is properly viewed as a programming language for use in constructing program modules that accomplish level-1 analysis as presented in the previous section. This development environment provides for direct input of GIS map layers as well as short-term *contextual* attribute values as factors for determining land suitability indices. System output is in the form of GIS map layers indicating posterior probabilities for various impact levels resulting from given ambient conditions.

Consider the following scenario (adapted from Buehler and Wright, 1990a):

> A judgement must be made as to the likely impact of assigning, to a specific land area, a specific activity. Complete and accurate information is available about the nature of the activity, the physical and environmental nature of the candidate land area, and the conditions present at the time the activity is to take place. The person responsible for making the assignment wishes to develop a decision support system that will aid that decision. Given that the Bayesian model is deemed appropriate as the reasoning engine for this decision support system the following steps are required:

1. *A person knowledgeable about the activity to be assigned, the candidate land area, and the nature of impact cause-effect, designs a Bayesian model that captures the most important aspects of the specific problem, adhering to exclusivity and exhaustivity requirements.*
2. *Categorical probability data are collected for that model and probabilities are computed. This information is as-*

sumed to reflect the cause-effect nature of the activity under consideration to the extent that future observations about impact may be used to update these probabilities.

3. *A person knowledgeable about the mechanics of geographical information systems and the structure of the probability information acquired in step 2 produces a computer script program that reflects the model developed in step 1. This may require close interaction with the domain expert as well as the target user (if that is not the same person).*
4. *The script or program developed in step 3 is then used to control the execution of a system that will 1) prompt the user for input about short-term conditions that might influence land impact, 2) access GIS map layers for long-term environmental information over time and space, and 3) produce information about likely impact in the form of probability maps as reflected by the Bayesian model.*
5. *The spatial impact maps are used, possibly with other data and analytical procedures, to make the activity assignment.*
6. *Following the activity, a judgement as to the resulting impact is made and short-term conditions are recorded. This becomes an additional observation upon which to update the probabilities for that activity.*

The short-term conditions mentioned in the scenario are important to this discussion because in the case that these conditions didn't change there would be no need for a shell environment. The system could be executed one time and the output probability maps generated would suffice. The need to include contextual attributes (in some cases many of such attributes) demands an environment where the same application can be executed for any combination of these attributes. Applications with many contextual attributes could be implemented quickly and easily with a shell tools such as B-infer. Furthermore, the applications would be easily executed to aid in the activity assignment decision with the current values of all contextual attributes, so that the decision would always be based in part on the current judgement of impact.

Figure 3 presents a schematic diagram of B-infer. The application developer prepares the input script (referred to in the scenario above) placing it into a file using any system editor. The software is then executed within the GRASS environment. During execution B-infer reads the input script (arrow from Input Script to B-infer Software in the figure), and translates the information into an internal representation (see Buehler and Wright, 1990b). B-infer then obtains the value for contextual attributes by prompting the user using menus constructed from the input script (the bidirectional arrows from B-infer Software to the User in the figure). GRASS is then called upon to reclassify or recategorize the input maps corresponding to the ranges of layer attribute values given in the script[1]. For example, a map of soils may have many specific soil types represented, but we really only need a general soil type. A reclassification operation would recategorize existing soil types into a new, simplified description. These reclassified maps are then used as input to B-infer (the arrow from Reclassed Maps to GRASS Software and back to B-infer Software in Figure 3). Once B-infer has all of this information it can begin the inferencing process.

A new map is created for each possible value of the inferred attributes (the set of maps labeled Output Maps in Figure 3). The value in each cell represents the probability of that inferred attribute value occurring in that grid cell. These probability maps are then ready for input to some other decision-making process or system. B-infer also determines which value is most likely to occur in each grid cell and writes that to yet another cell file (the box labeled Combined Map in Figure 3). This combined map can be used to obtain an overall profile for the value of the inferred attribute over a land area.

5 Future directions

This research demonstrated that raster-based GIS technology combined with a formal Bayesian analysis system provides a SDSS environment for performing land suitability indexing in support of certain land allocation activities. In this context, the use of a Bayesian probabilistic inferencing model is only one possible procedure for assigning suitability. Other meaningful suitability assessment procedures might include a formal rule-based expert system with uncertainty incorporated as certainty factors or fuzzy logic, neural network procedures, frame based inferencing systems using formal hypothesis and test algorithms such as minimal set cover, and other statistical models such as the Dempster-Shafer theory of evidence. Work is presently under way on the development of these model components.

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[1] Maps within the GRASS GIS are structured as a matrix of integer values that are used to categorize attribute information. To reclassify or recategorize these maps involves a reassignment of the information..In the case of B-infer, categories may be generalized so that more detailed categorical descriptions are grouped into more general categories without data preprocessing.

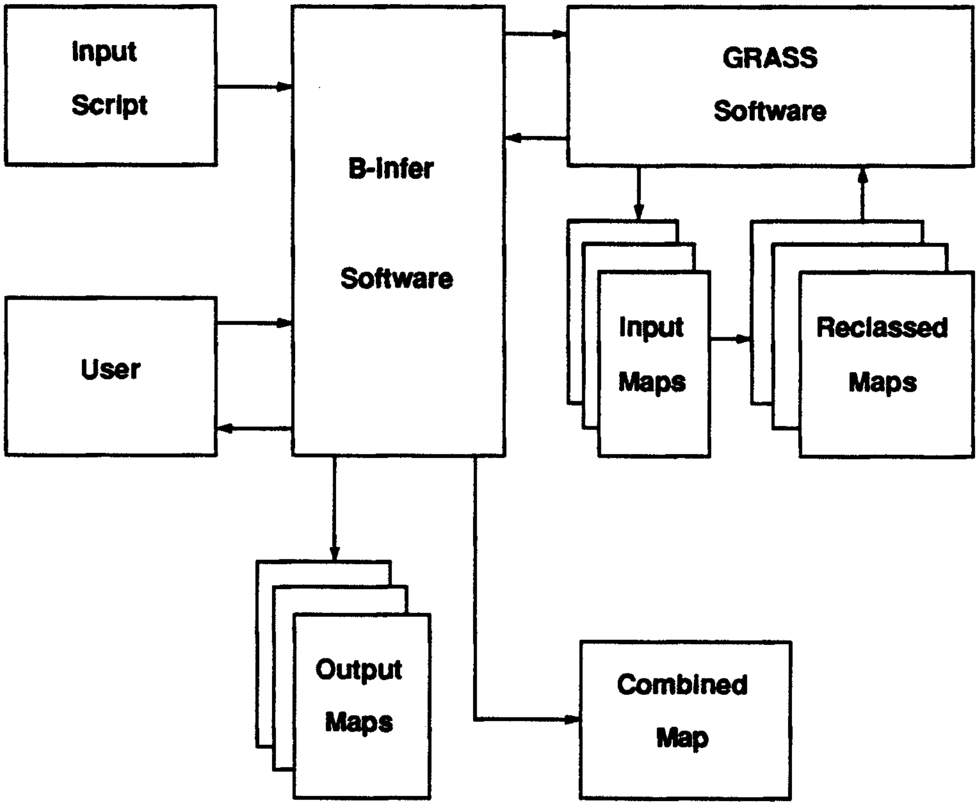

Figure 3 A schematic of the structure of the B-infer reasoning shell.

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