GIS Fundamentals:

A First Text on Geographic Information Systems

6th Edition

Paul Bolstad
University of Minnesota - Twin Cities

XanEdu

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GIS Fundamentals: A first text on geographic information systems,
6th edition.

Cover image courtesy NASA, from the ASTER instrument, Terra Satellite, of the Ubinas volcano, April, 2014.

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800-562-2147
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1 An Introduction to GIS

Introduction

Geography has always been important to humans. Stone-age hunters anticipated the location of their quarry, early explorers lived or died by their knowledge of geography, and current societies work and play based on their understanding of who belongs where. Applied geography, in the form of maps and spatial information, has served discovery, planning, cooperation, and conflict for at least the past 3,000 years (Figure 1-1). Maps are among the most beautiful and useful documents of human civilization, and spatial information has a great impact on our lives by helping us produce the food we eat, the energy we burn, the clothes we wear, and the diversions we enjoy.

Figure 1-1: A map of the mouth of the St. Lawrence River, most probably by Clement Lempiere, published in 1733. The river mouth is in the center, New Brunswick lower center, and Quebec across the top. Early maps were key to exploration (courtesy U.S. Library of Congress).

Because spatial information is so important, we have developed tools called geographic information systems (GIS) to aid us with geographic knowledge. A GIS helps us gather and use spatial data (we will use the abbreviation GIS to refer to both singular, system, and plural, systems). Some GIS components are purely technological; these include space-age data collectors, advanced communications networks, and sophisticated computing. Other GIS components are very simple, for example, a pencil and paper used to field-verify a map.

As with many aspects of life in the last five decades, how we gather and use spatial data has been profoundly altered by modern electronics, and GIS software and hardware are primary examples of these technological developments. The capture and analysis of spatial data has accelerated over the past four decades, and continues to evolve.

Key to all definitions of a GIS are "where" and "what." GIS record the absolute and relative location of features, as well as the properties and attributes of those features. Mount Everest is in Asia, Timbuktu is in Mali, and the cruise ship *Titanic* is at the bottom of the Atlantic Ocean. A GIS quantifies these locations by recording their *coordinates*, numbers that describe the position of these features on Earth. The GIS may also be used to record the height of Mount Everest, the population of Pierre, or the depth of the *Titanic*, as well as any other defining characteristics of each spatial feature.

What is a GIS?

A GIS is a tool for making and using spatial information. Among the many definitions of GIS, we choose:

> *A GIS is a computer-based system to aid in the collection, maintenance, storage, analysis, output, and distribution of spatial data and information.*

When used wisely, GIS can help us live healthier, wealthier, and safer lives.

Each GIS user may decide what features are important, and what attributes are worth recording. For example, forests are important to many of us. They may protect water supplies, yield wood, harbor wildlife, and provide space to recreate (Figure 1-2).

Figure 1-2: GIS allow us to analyze important geographic features. The satellite image at the center shows a forested area in western Oregon, with a patchwork of lakes, forests, clearings, alpine zones, and deserts. A GIS may aid in ensuring sustainable recreation, timber harvest, environmental protection, and other benefits (courtesy NASA).

We are concerned about the level of harvest, the adjacent land use, pollution from nearby industries, or where forests burn. Informed management requires knowledge of all these related factors and, perhaps above all, the spatial arrangement of these factors. Buffer strips near rivers may protect water supplies, clearings may prevent the spread of fire, and polluters downwind may not harm our forests while polluters upwind might. A GIS helps us analyze these spatial interactions, and is also particularly useful at displaying spatial data and analysis. A GIS is often the only way to solve spatially-related problems.

Why We Need GIS

GIS are essential tools in business, government, education, and nonprofit organizations, and GIS use has become mandatory in many settings. GIS have been used to fight crime, protect endangered species, reduce pollution, cope with natural disasters, treat epidemics, and improve public health; in short, GIS have been instrumental in addressing some of our most pressing societal problems.

GIS tools in aggregate save billions of dollars annually in the delivery of governmental and commercial goods and services. GIS regularly help in the day-to-day management of many natural and man-made resources, including sewer, water, power, and transportation networks. GIS are at the heart of one of the most important processes in U.S. democracy, the constitutionally mandated reshaping of U.S. congressional districts, and hence the distribution of tax dollars and other government resources.

GIS are needed in part because human populations and consumption have reached levels such that many resources, including air and land, are placing substantial limits on human action (Figure 1-3). Human populations have doubled in the last 50 years, surpassing 7 billion, and we will likely add another 4 billion humans in the next 50 years. The first 100,000 years of human existence caused scant impacts on the world's resources, but in the past 300 years humans have permanently altered most of

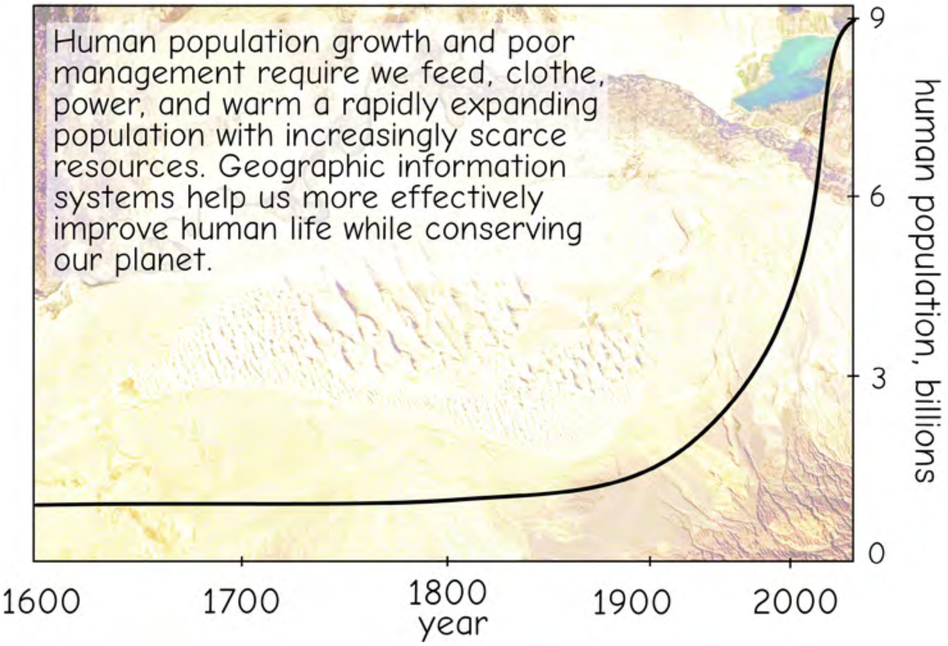


Figure 1-3: Human population growth during the past 400 years has increased the need for efficient resource use (courtesy United Nations and Ikonos).

the Earth's surface. The atmosphere and oceans exhibit a decreasing ability to benignly absorb carbon dioxide and nitrogen, two primary waste products of humanity. Silt chokes many rivers, and there are abundant examples of smoke, ozone, or other noxious pollutants substantially harming public health. By the end of the 20th century, most lands south of the boreal region had been farmed, grazed, cut, built over, drained, flooded, or otherwise altered by humans (Figure 1-4).

GIS help us identify and address environmental problems by providing crucial information on where problems occur and who are affected by them. GIS help us identify the source, location, and extent of adverse environmental impacts, and may help us devise practical plans for monitoring, managing, and mitigating environmental damage.

Human impacts on the environment have spurred a strong societal push for the adoption of GIS. Conflicts in resource use, concerns about pollution, and precautions to protect public health have led to legislative mandates that explicitly or implicitly require the consideration of geography. The U.S. Endangered Species Act of 1973 (ESA) is an example of the importance of geography in resource management. The ESA requires adequate protection of rare and threatened organisms. Effective protection entails mapping the available habitat and analyzing species range and migration patterns. The location of viable remnant plant and animal populations relative to current and future human land uses must be analyzed, and action taken to ensure species survival. GIS have proven to be useful tools in all of these tasks. GIS use is mandated in other endeavors, including emergency services, flood protection, disaster assessment and management (Figure 1-5), and infrastructure development.

Public organizations have adopted GIS because of legislative mandates, and because GIS aid in governmental functions. For example, emergency service vehicles are regularly dispatched and routed using GIS. E911 callers and addresses are automatically identified by telephone number. The GIS matches the address to the nearest emergency service station, a route is then immediately generated based on the street network and traffic, and emergency crews dispatched from the nearest station.

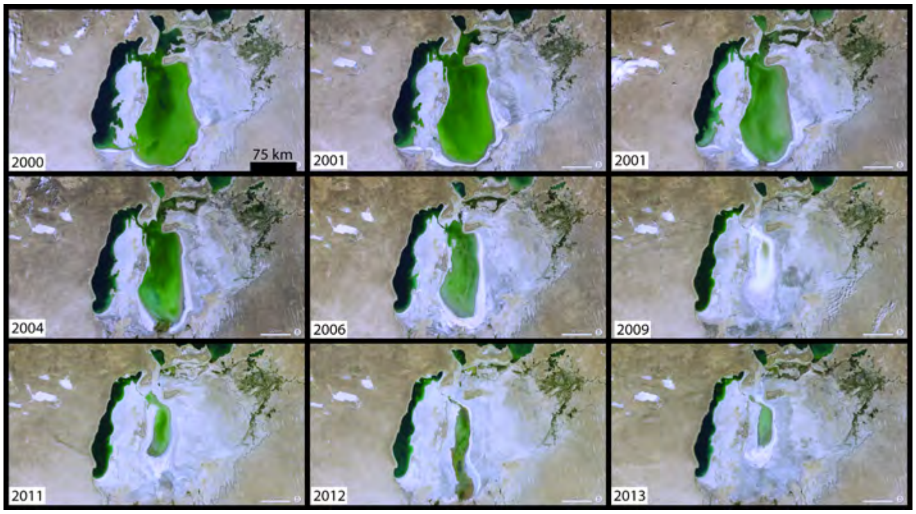


Figure 1-4: The environmental impacts wrought by humans have accelerated in many parts of the world during the past century. These satellite images from 2000 (upper left) to 2013 (lower right) show a shrunken Aral Sea due to the overuse of water. Diversion for irrigation has destroyed a rich fishery, the economic base for many seaside communities. GIS may be used to document change, mitigate damage, and effectively manage our natural resources (courtesy NASA).

Figure 1-5: GIS may aid in disaster assessment and recovery. These satellite images from Banda Aceh, Indonesia, illustrate tsunami-caused damage to a shoreline community. Emergency response and longer-term rebuilding efforts may be improved by spatial data collection and analysis (courtesy DigitalGlobe).

Many businesses adopt GIS for increased efficiency in the delivery of goods and services. Retail businesses locate stores based on a number of spatially related factors. Where are the potential customers? What is the spatial distribution of competing businesses? Where are potential new store locations? What are traffic flows near current stores, and how easy is it to park near and access these stores? GIS are also used in hundreds of other business applications, to route delivery vehicles, guide advertising, design buildings, plan construction, and sell real estate.

The societal push to adopt GIS has been complemented by a technological pull in the development and application of GIS. Thousands of lives and untold wealth have been lost because ship captains could not answer the simple question, “Where am I?” Robust nautical navigation methods emerged in the 18th century, and have continually improved since, so that anyone can quickly locate their outdoor position to within a few meters. Remarkable positioning technologies, generically known as Global Navigation Satellite Systems (GNSS), are now indispensable tools in commerce, planning, and safety.

The technological pull has developed on several fronts. Spatial analysis in particular has been helped by faster computers with more storage, and by the increased interconnectedness via WiFi and mobile networks. Most real-world spatial problems were beyond the scope of all but the largest government and business organizations until the 1990s. GIS computing expenses are becoming an afterthought, as computing resources often cost less than a few weeks’ salary for a qualified GIS professional.Costs decrease and performance increases at dizzying rates, with predicted plateaus pushed back each year. Powerful field computers are lighter, faster, more capable, and less expensive, so spatial data display and analysis capabilities may always be at hand (Figure 1-6).

GIS on rugged, field-portable computers has been particularly useful in field data entry and editing.

In addition to the computing improvements and the development of GNSS, current "cameras" deliver amazingly detailed aerial and satellite images. Initially, advances in image collection and interpretation were spurred by World War II and then the Cold War because accurate maps were required, but unavailable. Turned toward peacetime endeavors, imaging technologies now help us map food and fodder, houses and highways, and most other natural and human-built objects. Images may be rapidly converted to accurate spatial information over broad areas (Figure 1-7). Many techniques have been developed for extracting information from image data, and also for ensuring this information faithfully represents the location, shape, and characteristics of features on the ground. Visible light, laser, thermal, and radar scanners are currently being developed to further increase the speed and accuracy with which we map our world. Thus, advances in these three key technologies — imaging, GNSS, and computing — have substantially aided the development of GIS.

Figure 1-6: Portable computing is one example of the technological pull driving GIS adoption (courtesy Cogent3D, www.GISRoam.com).

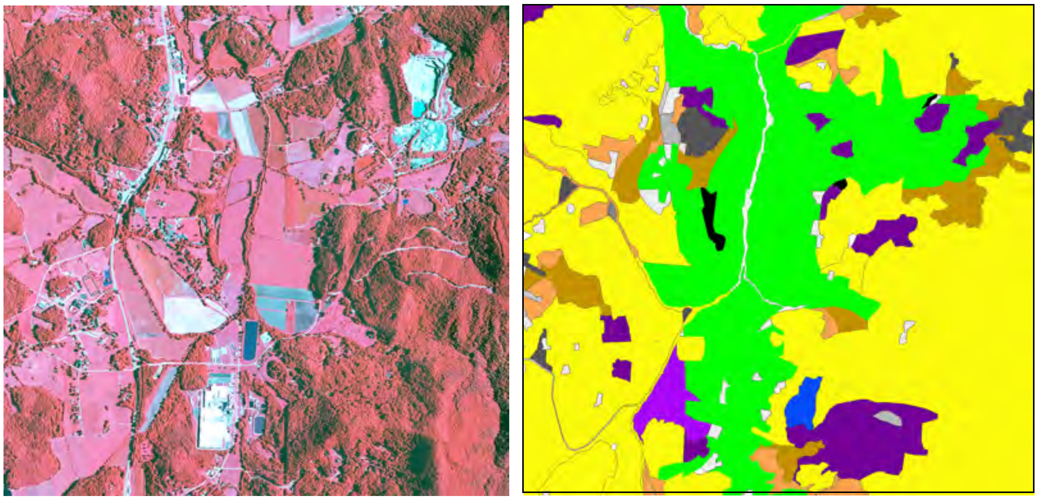


Figure 1-7: Images taken from aircraft and satellites (left) provide a rich source of data, which may be interpreted and converted to information about the Earth's surface (right).

GIS in Action

Spatial data organization, analyses, and delivery are widely applied to improve life. Here we describe examples that demonstrate how GIS are in use.

Marvin Matsumoto was saved with the help of GIS. The 60-year-old hiker became lost in Joshua Tree National Park, a 300,000-hectare desert landscape famous for its distinct and rugged terrain. Between six and eight hikers become lost there in a typical year, sometimes fatally so. Because of the danger of hypothermia, dehydration, and death, the U.S. National Park Service (NPS) organizes search and rescue operations that include foot patrols, horseback, vehicle, and helicopter searches (Figure 1-8).

The search and rescue operation for Mr. Matsumoto was organized and guided using GIS. Search and rescue teams carried field positioning devices that recorded team location and progress. Position data were downloaded from the field devices to a field GIS center, and frequently updated maps were produced. On-site incident managers used these maps to evaluate areas that had been searched, and to plan subsequent efforts in real time. Accurate maps showed exactly what portions of the park had been searched and by what method. Appropriate teams were tasked to unvisited areas. Ground crews could be assigned to areas that had been searched by helicopters, but contained vegetation or terrain that limited visibility from above. Marvin was found on the fifth day, alive but dehydrated and with an injured skull and back from a fall. The search team was able to radio its precise location to a rescue helicopter. Another day in the field and Marvin likely would have died, a day saved by the effective use of GIS.

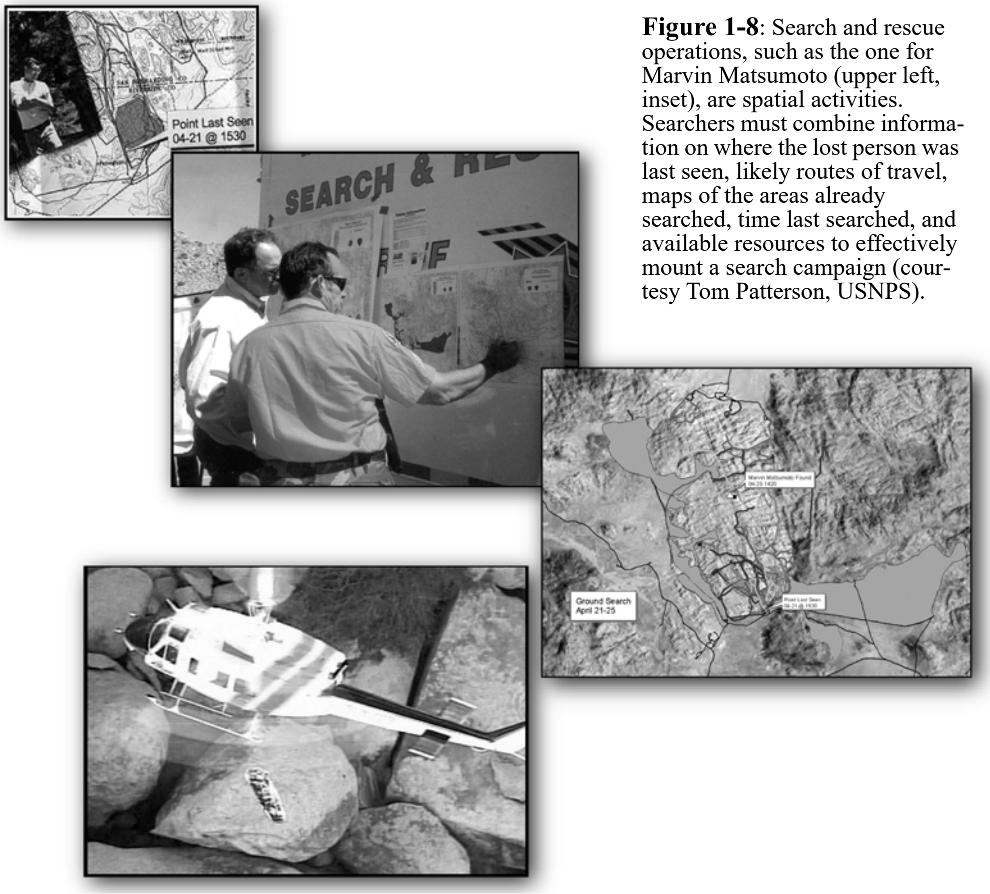


Figure 1-8: Search and rescue operations, such as the one for Marvin Matsumoto (upper left, inset), are spatial activities. Searchers must combine information on where the lost person was last seen, likely routes of travel, maps of the areas already searched, time last searched, and available resources to effectively mount a search campaign (courtesy Tom Patterson, USNPS).

GIS are also widely used in planning and environmental protection. Oneida County is located in northern Wisconsin, a forested area characterized by exceptional scenic beauty. The county is in a region with among the highest concentrations of freshwater lakes in the world, a region that is also undergoing a rapid expansion in the permanent and seasonal human populations. Retirees, urban exiles, and vacationers are increasingly drawn to the scenic and recreational amenities available in Oneida County. Permanent county population grew by nearly 30% from 1990 to 2010, and the seasonal influx almost doubles the total county population each summer.

Population growth has caused a boom in construction and threatened the lakes that draw people to the county. A growing number of building permits are for nearshore houses, hotels, or businesses. Seepage from septic systems, runoff from fertilized lawns, or erosion and sediment from construction all decrease lake water quality. Increases in lake nutrients or sediment may lead to turbid waters, reducing the beauty and value of the lakes and nearby properties.

In response to this problem, Oneida County, the Sea Grant Institute of the University of Wisconsin, and the Land Information and Computer Graphics Facility of the University of Wisconsin have developed a Shoreland Management GIS Project. This project helps protect valuable nearshore and lake resources, and provides an example of how GIS tools are used for water resource management (Figure 1-9).

Oneida County has revised zoning and other ordinances to protect shoreline and lake quality, and to ensure compliance without undue burden on landowners. The county uses GIS technology in the maintenance of property records. Property records include information on the owner, tax value, and any special zoning considerations. The county uses these digital records when creating parcel maps; processing sale, subdivision, or other parcel transactions; and integrating new data such as aerial or boat-

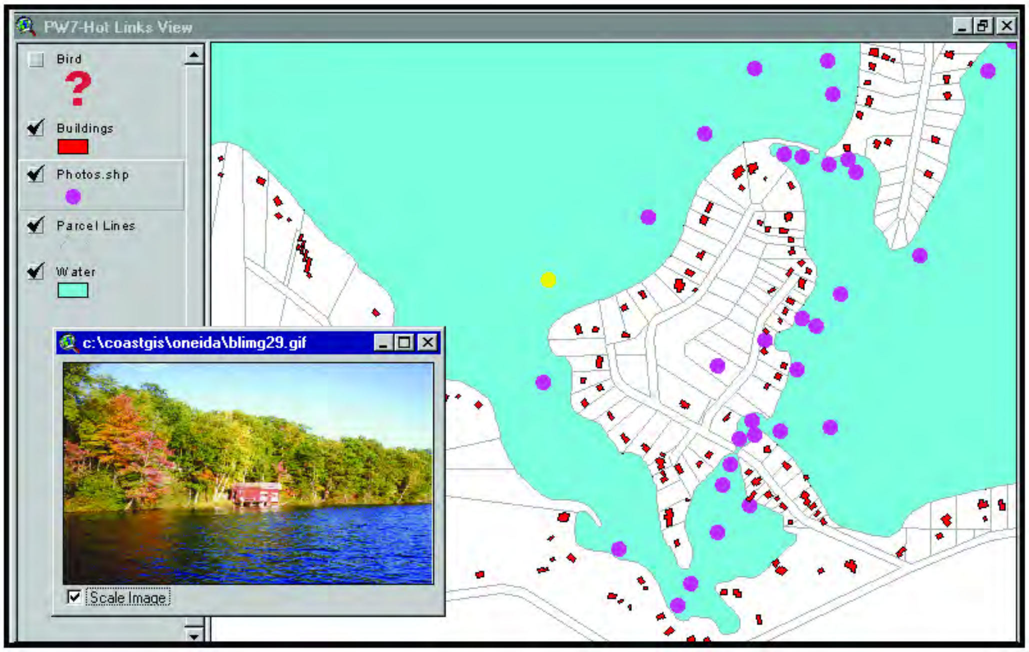
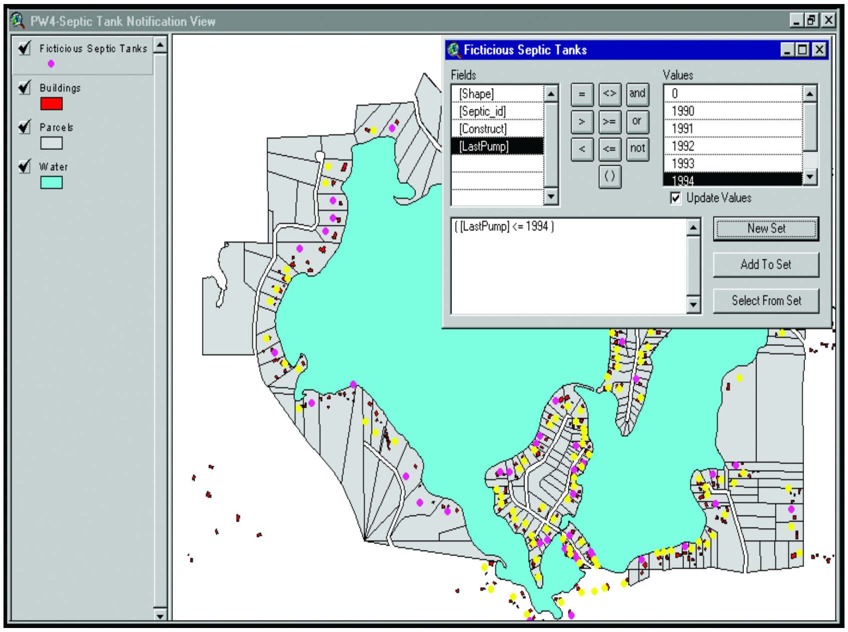


Figure 1-9: Parcel information entered in a GIS may substantially improve government services. Here, images of the shoreline taken from lake vantage points are combined with digital maps of the shoreline, buildings, and parcel boundaries. The image in the lower left was obtained from the location shown as a light dot near the center of the figure (courtesy Wisconsin Sea Grant Institute and LICGF).



([LastPump] <= 1994)

Figure 1-10: GIS may be used to streamline government function. Here, septic systems not compliant with pollution prevention ordinances are identified by light circles (courtesy Wisconsin Sea Grant Institute and LICGF).

based images to help detect property changes and zoning violations.

GIS may also be used to administer shoreline zoning ordinances, or to notify landowners of routine tasks, such as septic system maintenance. Northern lakes are particularly susceptible to nutrient pollution from nearshore septic systems (Figure 1-10). Timely maintenance of each septic system must be verified. The GIS can automatically identify owners out of compliance and generate an appropriate notification.

GIS has helped the U.S. Fish and Wildlife Service manage the recovery of the Gray Wolf (*Canis lupus*) in the lower 48 states of the United States. Wolves were hunted to a remnant population in northern Minnesota. Given protection in 1974, the population has rebounded to nearly 6,000 wolves that are spread across at least 11 states. GIS helped in many phases of the recovery, including identifying suitable habitat, monitoring pack location through time, mapping prey abundance and areas of high potential conflict with humans due to land use (e.g., ranching), assessing the impacts of range recovery on

Figure 1-11: A gray wolf, one of a few successfully recovered endangered species, restored with the help of GIS (courtesy Spinus Art Photos).

Figure 1-12: Wolf recovery involved tranquilizing and fitting wolves with tracking collars. These provide detailed location and movement data, and a better understanding of wolf habitat requirements (courtesy NPS).

other resources (deer and other game), and natural limits to range expansion

Relatively new spatial data capture technologies are used to help in wolf recovery. Animals are tranquilized, fitted with satellite tracking collars, and released (Figure 1-13). These collars may create an hour by hour record of wolf location, giving precise information on habitat occupancy, movement rates, hunting vs. resting time, optimal denning sites, and dispersal. More data are provided in a few weeks by these satellite tracking collars than were possible with a decade of collection using the older, radio-based technologies they replaced.

Scientists at the Voyageurs Wolf Project have been tracking wolves to better understand their behavior (Figure 1-13). Part of wolf recovery and de-listing may include hunting and trapping seasons in some areas. Harvest isn't allowed in U.S. National Parks, but may be on adjacent lands, e.g., State and National Forests. Removing pack members may affect a pack's ability to group hunt, reproduce, or defend their territory. Wolves may respond to hunting pressure by moving further into parks, in turn displacing adjacent packs. Analysis of pack location and movements during trial hunting and trapping may help guide a sustainable recovery.

GIS are widely used to improve public health. Air pollution is a major cause of sickness and death, primarily from nitrogen and sulfur dioxides, carbon monoxide, ozone, and small particles from oil, gas, coal, and

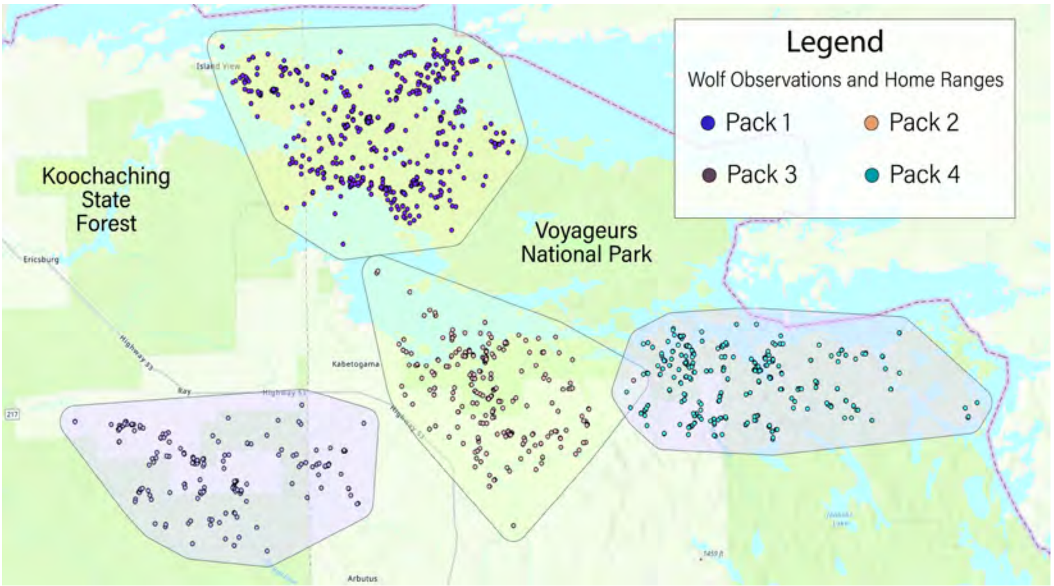


Figure 1-13: Spatial data, such as the recorded pack locations and home ranges (circles and polygons, respectively), may be combined to help understand how best to manage the Gray Wolf (courtesy Voyageurs Wolf Project).

Figure 1-14: Air pollution from power plants and vehicles is still a significant health hazard (courtesy M. Riya and the State of California).

wood combustion. Primary sources are power generation, factories, and transporation (Figure 1-14). Small particles lodge in the lungs , causing inflammation and reducing lung function (Figure 1-15). Alveolar macrophages attempt to isolate this material, but air pollution levels commonly exceed the lung's capacity for self-cleaning. Damaging particle concentrations are typically higher in urban areas, or near traffic, power plants, and other pollution sources. GIS helps map concentrations, identify sources, and plan improvements. Air pollution shaves 10 years off of the life span of about 200,000 people in the United States each year, and is responsible for the death of 7 million people worldwide each year. It also causes increased sickness, hospitalization, and medical costs that annually reach into the billions of dollars. A reduction in air pollution has been shown to significantly reduce hospitalization, childhood asthma, and to increase life expectancy.

Reducing sickness and death requires identifying areas of high exposure, particularly for vulnerable populations. Effective management requires an estimate of how much a decrease in pollution will increase health. Scientists have focused on these questions over the past decades, and can map exposures both over broader areas and at increasing level of spatial detail.

Air pollution may be mapped from satellites, as the chemicals and particles change the optical properties of air (Figure 1-16, top). A number of satellite instruments, culminating in the Ozone Mapping and Profiling Suite (OMPS), have been launched over the past 30 years to record air quality. Painstaking engineering, testing, and comparison to ground and airborne measurements have verified instrument accuracies. This has led

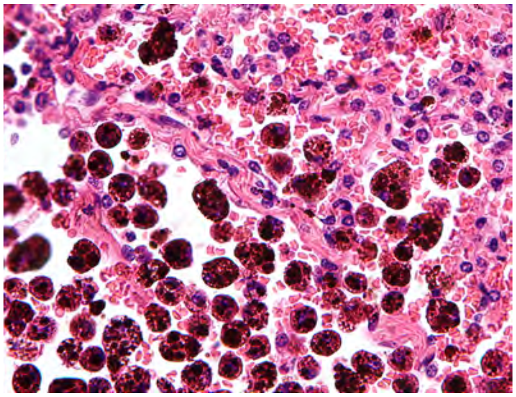


Figure 1-15:: Small air pollution particles (dark spots, above) lodge in lungs and cause life-long damage (courtesy Nephron).

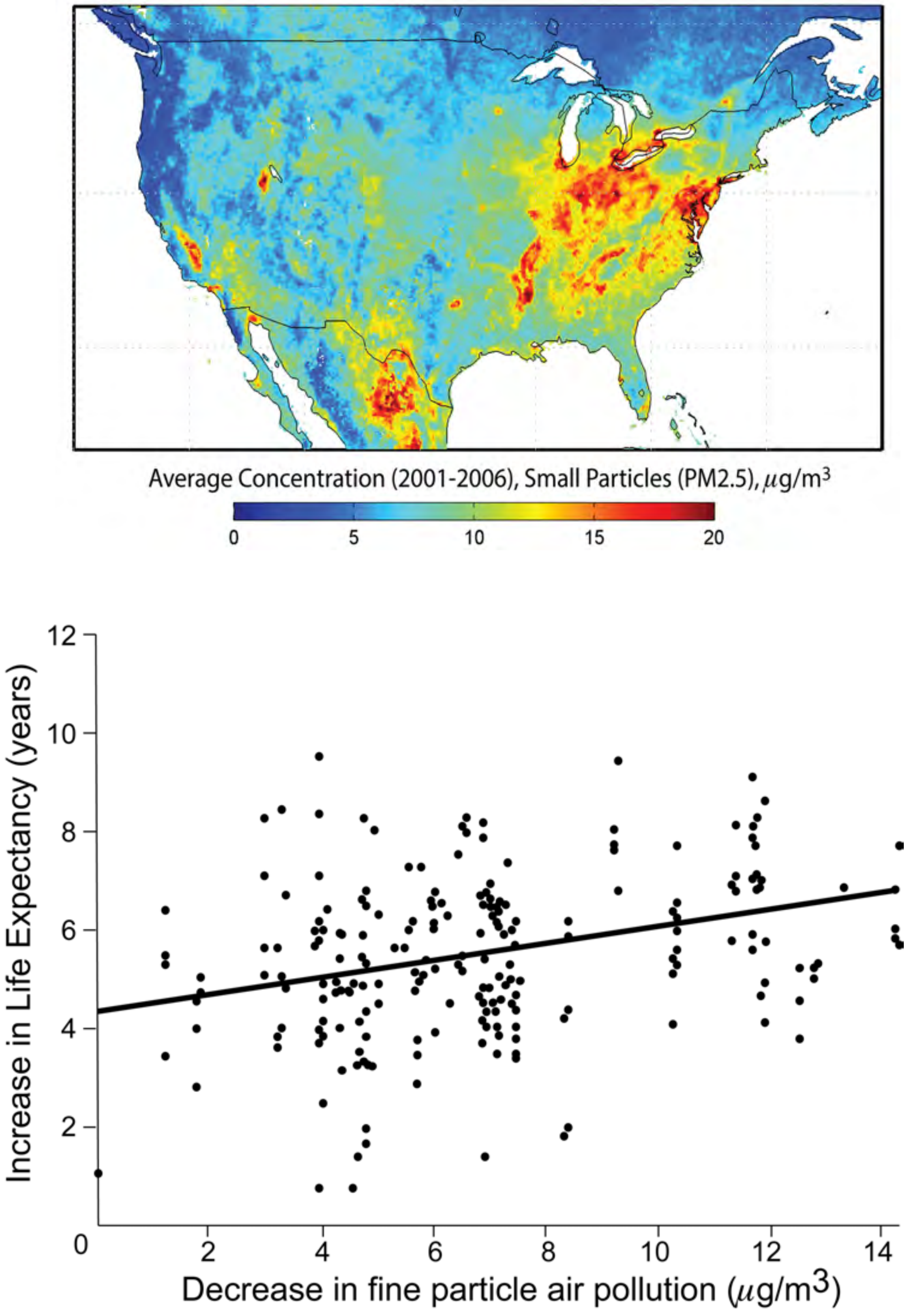


Figure 1-16: Scientists at NASA have developed methods to map air pollution across continents on a daily basis, which may be averaged to estimate chronic exposure (top). These spatial data may be combined with studies on human response to air pollution (bottom) and the location of vulnerable populations to improve public health and reduce medical costs.

to a long-term record of pollutant concentrations, and improved understanding of the sources and dynamics of pollutants across regional through global geographies. These data allow measurement of peak and chronic exposure to pollutants for different populations. They show persistent areas of high exposure (Figure 1-16), some concentrated in cities, largely due to automobile traffic, and others over large areas, e.g., the Midwest, due to large coal-fired power plants and industrial sources. Some areas are particularly prone to high concentrations due to surrounding highlands, e.g., the Central Valley of California or Salt Lake City, Utah.

Work by health scientists has identified the specific impacts of air pollution by analyzing response in target populations. Increased rates of asthma, lung damage, and death observed in smaller studies or individual cities can be expanded to broader areas through the combination of data in GIS. For example, combining health and population data with satellite exposure records has helped estimate the increase in life expectancy with a decrease in air pollution. Legislation passed in the 1970s resulted in a measurable improvement in air quality across the United States. Progress has been variable across the country, with some populations seeing larger reductions. Scientists measured the decrease in death rates in comparable populations, and estimated an average 2-year increase in life span for each 10 µg-m^{-3} reduction in exposure (Figure 1-16, bottom).

Additional work has focused on air pollution at greater geographic detail, in part to better quantify and manage individual exposure and risk. Dr. Julian Marshall and collaborators at the University of Minnesota have developed systems to sample pollutant concentrations at very fine spatial intervals, towing an air sampling system behind a bicycle through a range of traffic densities, road types, and neighborhoods (Figure 1-17). Satellite positioning was synchronized with video and air samples, and these com-

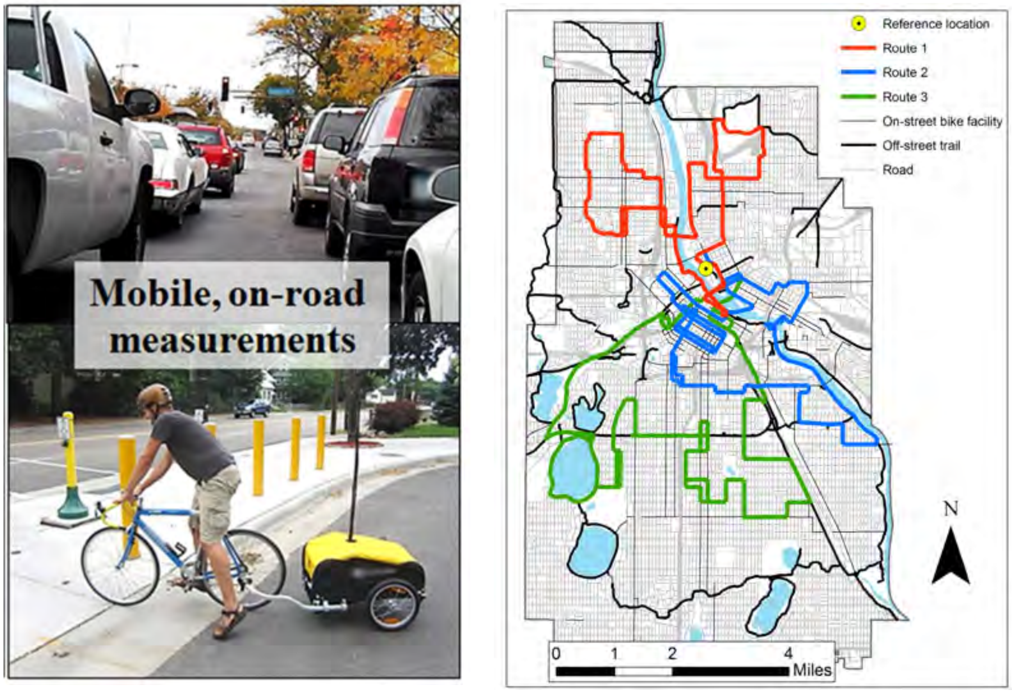


Figure 1-17: Towable samplers help measure air pollution for individual streets, at various traffic densities and types (courtesy J. Marshall).

bined with spatial data on road networks, population density, land use, and other factors. Statistical models were then developed. These allow detailed estimates of pollutant concentrations, even down to the individual street (Figure 1-18). Such estimates may in turn help reduce air pollution, plan bicycle or pedestrian corridors, separate the pollutant loadings due to cars vs. trucks, buses or other large vehicles, and manage traffic or infrastructure to reduce human exposure.

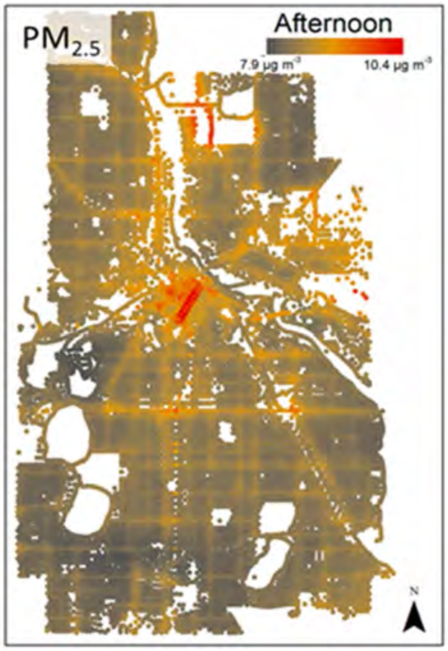


Figure 1-18: Fine-detailed spatial estimates of particulate air pollutants (courtesy J. Marshall).

GIS Components

A GIS is composed of hardware, software, data, humans, and a set of organizational protocols. These components must be well integrated for effective use of GIS, and the development and integration of these components is an iterative, ongoing process. The selection and purchase of hardware and software is often the easiest and quickest step in the development of a GIS. Data collection and organization, personnel development, and the establishment of protocols for GIS use are often more difficult and time-consuming endeavors.

Hardware for GIS

A fast computer, large data storage capacities, and a high-quality, large display form the hardware foundation of most GIS (Figure 1-19). A fast computer is required because spatial analyses are often applied over large areas and/or at high spatial resolutions. Calculations often have to be repeated over tens of millions of times, corresponding to each space we are analyzing in our geographical analysis. Even simple operations may take substantial time on general-purpose computers when run over large areas, and complex operations can be unbearably long-running. While advances in computing technology during the past decades have substantially reduced the time required for most spatial analyses, computation times are still unacceptably long for a few applications.

While most computers and other hardware used in GIS are general-purpose and adaptable for a wide range of tasks, there are also specialized hardware components that are specifically designed for use with spatial data. GIS require large volumes of data that must be entered to define the shape and location of geographic features, such as roads, rivers, and parcels. Specialized equipment, described in Chapters 4 and 5, has been developed to aid in these data entry tasks.

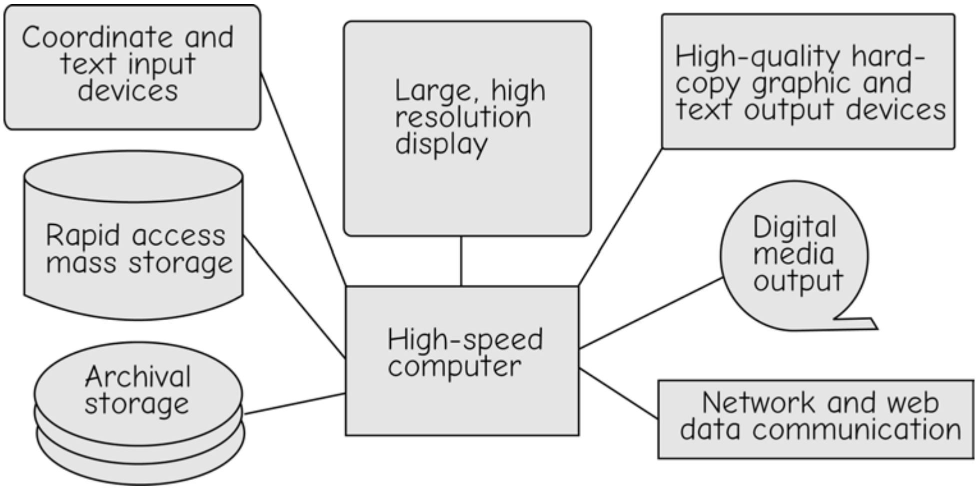


Figure 1-19: GIS are typically used with a number of general-purpose and specialized hardware components.

GIS Software

GIS software provides the tools to manage, analyze, and effectively display and disseminate spatial information (Figure 1-20). GIS by necessity involves the collection and manipulation of coordinates. We also must collect qualitative or quantitative information on the nonspatial attributes of geographic features. We need tools to view and edit these data, manipulate them to generate and extract the information we require, and produce the materials to communicate the information we have developed. GIS software provides the specific tools for some or all of these tasks.

There are many public domain and commercially available GIS software packages, and many of these packages originated at academic or government-funded research laboratories. The Environmental Systems Research Institute (ESRI) line of products, including ArcGIS, is a good example. Much of the foundation for early ESRI software was developed during the 1960s and 1970s at Harvard University in the Laboratory of Computer Graphics and Spatial Analysis. Alumni from Harvard included these in commercial products, and have developed additional methods and integrated new academic research in the five decades since.

Open Geospatial Consortium

We will briefly cover the most common GIS software, but first wish to introduce the Open Geospatial Consortium (OGC). Their efforts have eased sharing across various GIS softwares and computer operating systems. Standards for data formats, documentation, program interactions, and transmission have been developed and published (www.opengeospatial.org), and lists of standards-compliant software compiled. While some data structures remain opaque or proprietary, most have become open, and common standards ease community adoption, reduce barriers to switching among softwares, or adopting multiple geospatial processing packages. Compliance with the standards is a plus from a user's perspective, so a quick review of the OGC-compliant list is recommended when selecting a software platform.

Data entry
- manual coordinate capture
- attribute capture
- digital coordinate capture
- data import

Editing
- manual point, line and area feature editing
- manual attribute editing
- automated error detection and editing

Data management
- copy, subset, merge data
- versioning
- data registration and projection
- summarization, data reduction
- documentation
- compression
- indexing

Analysis
- spatial query
- attribute query
- interpolation
- connectivity
- proximity and adjacency
- buffering
- terrain analyses
- boundary dissolve
- spatial data overlay
- moving window analyses
- map algebra

Output
- map design and layout
- hardcopy map printing
- digital graphic production
- export format generation
- metadata output
- digital map serving

Figure 1-20: Functions commonly provided by GIS software.

Our software descriptions include the most widely used software packages, but are not all-inclusive. There are many additional software tools and packages available, particularly for specialized tasks or subject areas.

ArcGIS

ArcGIS, in its various online, desktop, and server versions, comprises the most popular GIS software suite at the time of this writing. ESRI, the developer of ArcGIS, has a worldwide presence. ESRI has been producing GIS software since the early 1980s, and ArcGIS is its most recent and well-developed integrated GIS package. In addition to software, ESRI also provides substantial training, support, and fee-consultancy services at regional and international offices.

ArcGIS is designed to provide a large set of geoprocessing procedures, from data entry through analysis to most forms of data output. As such, ArcGIS is a large, complex, sophisticated product. It supports multiple data formats, many data types and structures, and literally thousands of possible operations that may be applied to spatial data. It is not surprising that substantial training is required to master the full capabilities of ArcGIS.

ArcGIS provides wide flexibility in how we conceptualize and model geographic features. Geographers and other GIS-related scientists have conceived of many ways to think about, structure, and store information about spatial objects. ArcGIS provides for the broadest available selection of these representations. For example, elevation data may be stored in at least four major formats, each with attendant advantages and disadvantages. There is equal flexibility in the methods for spatial data processing. This broad array of choices, while responsible for the large investment in time required for mastery of ArcGIS, provides concomitantly substantial analytical power.

QGIS

QGIS is an open-source software project, an initiative under the Open Source Geospatial Foundation. The software is a collaborative effort by a community of developers and users. QGIS is free, stable, changes smoothly through time, with the source code available so that it can be extended as needed for specific tasks. It provides a graphical user interface, supports a wide variety of data types and formats, and runs on Unix, MacOSX, and Microsoft Windows operating systems. As with most open-source software, the original offering had limited capabilities. With an average of approximately two updates a year since 2002, QGIS provides a large number of basic GIS display and analysis functions. An interface has been developed with GRASS, another open-source GIS with complementary analytical functions, but that lacks as straightforward a graphical user interface.

GeoMedia

GeoMedia and related products are the popular GIS suite from Hexagon Geospatial. GeoMedia offers a complete set of data entry, analysis, and output tools. A comprehensive set of editing tools may be purchased, including those for automated data entry and error detection, data development, data fusion, complex analyses, and sophisticated data display and map composition.

GeoMedia is particularly adept at integrating data from divergent sources, formats, and platforms. Intergraph appears to have dedicated substantial effort toward the OpenGIS initiative, a set of standards to facilitate cross-platform and cross-software data sharing. Data in any of the common commercial databases may be integrated with spatial data from many formats. Image, coordinate, and text data may be combined.

GeoMedia also provides a comprehensive set of tools for GIS analyses. Complex spatial analyses may be performed, including queries, for example, to find features in the database that match a set of conditions, and spatial analyses such as proximity or overlap between features. World Wide Web and mobile phone applications are well supported.

MapInfo

MapInfo is a comprehensive set of GIS products developed by the MapInfo Corporation, but now a part of Pitney Bowes. MapInfo products are used in a broad array of endeavors, although use seems to be concentrated in many business and municipal applications. This may be due to the ease with which MapInfo components are incorporated into other applications. Data analysis and display components are supported through a range of higher language functions, allowing them to be easily embedded in other programs. In addition, MapInfo provides a flexible, stand-alone GIS product that may be used to solve many spatial analysis problems.

Specific products have been designed for the integration of mapping into various classes of applications. For example, MapInfo products have been developed for embedding maps and spatial data into wireless handheld devices such as telephones, data loggers, or other portable devices. Products have been developed to support internet mapping applications, and serve spatial data in World Wide Web-based environments. Extensions to specific database products such as Oracle are provided.

Idrisi

Idrisi is a GIS system developed by the Graduate School of Geography of Clark University, in Massachusetts. Idrisi differs from the previously discussed GIS software packages in that it provides both image processing and GIS functions. Image data are useful as a source of information in GIS. There are many specialized software packages designed specifically to focus on image data collection, manipulation, and output. Idrisi offers much of this functionality while also providing a large suite of spatial data analysis and display functions.

Idrisi has adopted a number of very simple data structures, a characteristic that makes the software easy to modify. Some of these structures, while slow and more space-demanding, are easy to understand and manipulate for the beginning programmer. The space and speed limitations have become less relevant with improved computers. File formats are well documented and data easy to access. The developers of Idrisi have expressly encouraged researchers, students, and users to create new functions for Idrisi. Idrisi is an ideal package for teaching students both to use GIS and to develop their own spatial analysis functions.

A suite of tools for earth system modeling has been developed on the Idrisi platform, and combined in the Tereset software system. Functions include land change modeling, habitat and biodiversity modeling, and climate change adaptation.

Manifold

Manifold is a relatively inexpensive GIS package with a surprising number of capabilities. Manifold combines GIS and some remote sensing capabilities. Basic spatial data entry and editing support are provided, as well as projections, basic vector and raster analysis, image display and editing, and output. The program is extensible through a series of software modules. Modules are available for surface analysis, business applications, internet map development and serving, database support, and advanced analyses.

Manifold GIS has focused on rapid computations for large spatial databases, and in providing sophisticated image editing capabilities in a spatially referenced framework. Portions of images and maps may be cut and pasted into other maps while maintaining proper geographic alignment. Transparency, color-based selection, and other capabilities common to image editing programs are included in Manifold GIS.

AUTOCAD MAP 3D

AUTOCAD is the world's largest-selling computer drafting and design package. Produced by Autodesk, Inc. of San Rafael, California, AUTOCAD began as an engineering drawing and printing tool. A broad range of engineering disciplines are supported, including surveying and civil engineering. Surveyors have traditionally developed and maintained the coordinates for property boundaries, and these are among the most important and often-used spatial data. AUTOCAD MAP 3D adds substantial analytical capability to the already complete set of data input, coordinate manipulation, and data output tools provided by AUTOCAD.

GRASS

GRASS, the Geographic Resource Analysis Support System, is a free, open-source GIS that runs on many platforms. The system was originally developed by the U.S. Army Construction Engineering Research Laboratory (CERL), starting in the early 1980s, when much GIS software was limited in access and applications. CERL followed an open approach to development and distribution, leading to substantial contributions by a number of university and other government labs. Development was discontinued by the military, and taken up by an open-source "GRASS Development Team," a self-identified group of people donating their time to maintain and enhance GRASS. The software provides a broad array of raster and vector operations, and is used in both research and applications worldwide. Detailed information and the downloadable software are available at http://grass.itc.it/index.php.

MicroImages

MicroImages produces TNTmips, an integrated remote sensing, GIS, and CAD software package. MicroImages also produces and supports a range of other related products, including software to edit and view spatial data, software to create digital atlases, and software to publish and serve data on the internet.

TNTmips is notable both for its breadth of tools and the range of hardware platforms supported in a uniform manner. MicroImages recompiles a basic set of code for each platform so that the look, feel, and functionality is nearly identical irrespective of the hardware platform used. Image processing, spatial data analysis, and image, map, and data output are supported uniformly across this range.

TNTmips provides an impressive array of spatial data development and analysis tools. Common image processing tools are available, including support of a broad number of file formats, image registration and mosaics, reprojection, error removal, subsetting, combination, and image classification. Vector and raster analyses are supported, including multi-layer combination, viewshed, proximity, and network analyses. Extensive online documentation is available, and the software is supported by an international network of dealers.

ERDAS

ERDAS (Earth Resources Data Analysis System) – now owned and developed by Hexagon Geospatial, a division of Intergraph – began as an image processing system. The original purpose of the software was to enter and analyze satellite image data. ERDAS led a wave of commercial products for analyzing spatial data collected over large areas. Product development was spurred by the successful launch of the U.S. Landsat satellite in the 1970s. For the first time, digital images of the entire Earth surface were available to the public.

The ERDAS software evolved to include a comprehensive set of tools for cell-based data analysis. Image data are supplied in a cell-based format. The "checkerboard" format used for image data may also be used to store and manipulate other spatial data.

ERDAS and most other image processing packages provide data output formats that are compatible with most common GIS packages. Many image processing software systems are purchased explicitly to provide data for a GIS. The support of ESRI data formats is particularly thorough in ERDAS. ERDAS GIS components can be used to analyze these spatial data.

ENVI

ENVI is another GIS software package with origins in digital image processing. Particular emphasis has been placed on tools for developing and managing elevation data from satellites and airborne platforms, crop monitoring, and automated feature extraction. This last capability streamlines the identification of individual objects, such as buildings, trees, road segments, or water bodies. Recent updates have focused on tools for processing images from small, unmanned aerial drones.

Bentley Map

Bentley Systems has developed spatial analysis software for mobile device through enterprise levels, with a strong focus on flexible, integrated infrastructure design and development. Although its origins are as a computer-assisted drafting and design program, Bentley has evolved into a general set of tools, including field data collection, photogrammetry, sophisticated map composition, database management, analysis, and reporting.

Bentley products are particularly focused on the built environment, including road, building, utility, and other large construction design, planning, and management. Tools include a comprehensive suite for property records, including surveying parcel data management, terrain analysis and calculations for excavation and earthworks, rainfall runoff analysis and drainage design, street and utility layout, and 3D viewing of design alternatives. Bentley also supports industry-specific tools, including mining and power generation systems and networks.

SuperMap

SuperMap is a Hong Kong based company that provides a broad range of GIS software, including desktop, cloud-based, vector, raster, and 3D analysis. Subsystems and configurations have been developed and applied for land records and information management, facilities management, government economic and statistical services and support, municipalities, and emergency response management. It provides excellent support of Japanese, Korean, and Chinese languages, and has among the largest market shares in East Asia.

Spatial R, Python, and GDAL

Generic programing, processing, and statistical analysis tools may be combined to provide most GIS functions, and include newer analytical methods not available in common commercial packages. R is an open source software project with many spatial packages. These support a rich set of spatial operations, particularly for spatial estimation. Python is a general-purpose programing language with several available spatial libraries. Notable among them are Shapely, Geopandas, and pySAL, containing a large set of spatial functions. GDAL is a standard set of spatial input/output and data processing functions, which may interfaces with both R and Python. Together, these tools support sophisticated GIS analysis.

This review of spatial data software is incomplete. There are many other software tools available which provide unique, novel, or particularly clever combinations of geoprocessing functions. Whitebox GAT, Smallworld, ILWIS, MapWindow, PCI, and qvSIG are just a few additional software packages with spatial data capabilities. In addition, there are thousands of add-ons, special-purpose tools, or specific modules that complement these products.

GIS in Organizations

Although new users often focus on GIS hardware and software components, we must recognize that GIS exist in an institutional context. Effective use of GIS requires an organization to support various GIS activities. Most GIS also require trained people to use them, and a set of protocols guiding how the GIS will be used. The institutional context determines what spatial data are important, how these data will be collected and used, and ensures that the results of GIS analyses are properly interpreted and applied. GIS share a common characteristic of many powerful technologies. If not properly used, GIS may lead to a significant waste of resources, and may do more harm than good. The proper institutional resources are required for GIS to provide all its potential benefits.

GIS are often employed as decision support tools (Figure 1-21). Data are collected, entered, and organized into a spatial database, and analyses performed to help make specific decisions. The results of spatial analyses in a GIS often uncover the need for more data, and there are often several iterations through the collection, organization, analysis, output, and assessment steps before a final decision is reached. It is important to recognize the organizational structure within which the GIS will operate, and how GIS will be integrated into the decision-making processes of the organization.

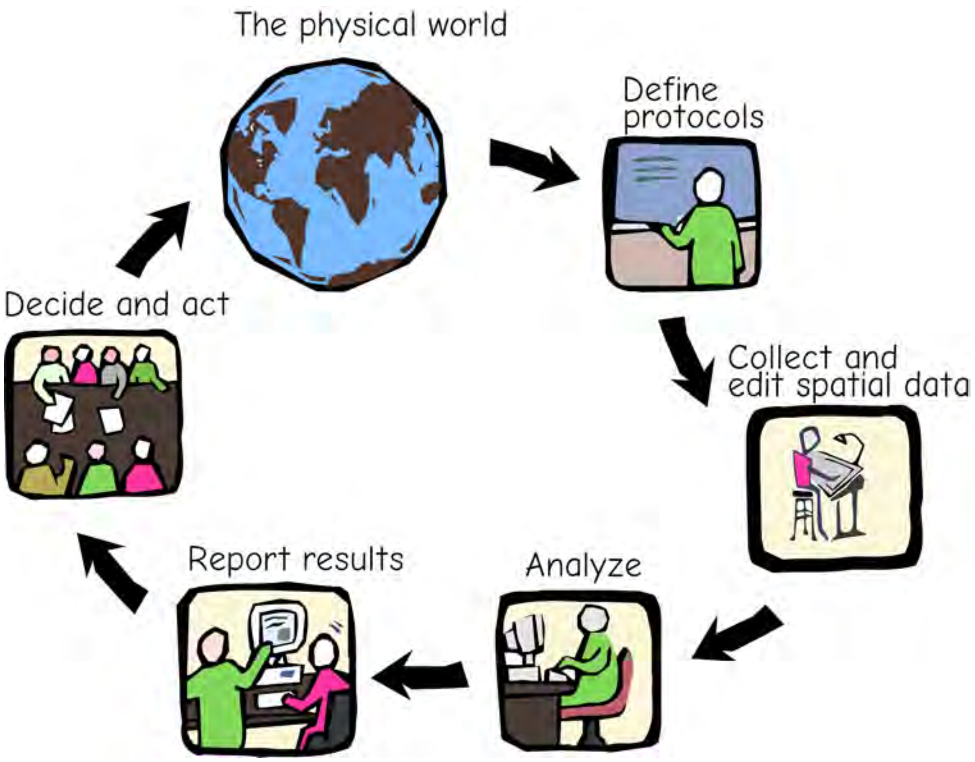


Figure 1-21: GIS exist in an institutional context. Effective use of GIS depends on a set of protocols and an integration into the data collection, analysis, decision, and action loop of an organization.

One first question is, “What problem(s) are we to solve with the GIS?” GIS add significant analytical power through the ability to measure distances and areas, identify vicinity, analyze networks, and through the overlay and combination of different information. Unfortunately, spatial data development is often expensive, and effective GIS use requires specialized knowledge or training, so there is often considerable expense in constructing and operating a GIS. Before spending this time and money, there must be a clear identification of the new questions that may be answered, or the process, product, or service that will be improved, made more efficient, or less expensive through the use of GIS. Once the ends are identified, an organization may determine the level of investment in GIS that is warranted.

Summary

GIS are computer-based systems that aid in the development and use of spatial data. There are many reasons we use GIS, but most are based on a societal push, our need to more effectively and efficiently use our resources. It also responds to a technological pull, our interest in applying new tools to previously insoluble problems. GIS as a technology is based on geographic information science, and is supported by the disciplines of geography, surveying, engineering, space science, computer science, cartography, statistics, and a number of others.

GIS are composed of both hardware and software components. Because of the large volumes of spatial data and the need to input coordinate values, GIS hardware often have large storage capacities, fast computing speed, and ability to capture coordinates. Software for GIS are unique in their ability to manipulate coordinates and associated attribute data. A number of software tools and packages are available to help us develop GIS.

While GIS are defined as tools for use with spatial data, we must stress the importance of the institutional context in which GIS fit. Because GIS are most often used as decision support tools, the effective use of GIS requires more than the purchase of hardware and software. Trained personnel and protocols for use are required if GIS are to be properly applied. GIS may then be incorporated in the question–collect–analyze–decide loop when solving problems.

The Structure of This Book

This book is designed to serve a semester-long, 15-week course in GIS at the university level. We seek to provide the relevant information to create a strong basic foundation on which to build an understanding of GIS. Because of the breadth and number of topics covered, students may be helped by knowledge of how this book is organized. Chapter 1 (this chapter) sets the stage, providing some motivation and a background for GIS. Chapter 2 describes basic data representations. It treats the main ways we use computers to represent perceptions of geography, common data structures, and how these structures are organized. Chapter 3 provides a basic description of coordinates and coordinate systems, how coordinates are defined and measured on the surface of the Earth, and conventions for converting these measurements to coordinates we use in a GIS.

Chapters 4 through 7 treat spatial data collection and entry. Data collection is often a substantial task and comprises one of the main activities of most GIS organizations. General data collection methods and equipment are described in Chapter 4. Chapter 5 describes Global Navigation Satellite Systems (GNSS), a common technology for coordinate data collection. Chapter 6 describes aerial and space-based images as a source of spatial data. Most historical and contemporary maps depend in some way on image data, and this chapter provides a background on how these data are collected and used to create spatial data. Chapter 7 provides a brief description of common digital data sources available in the United States, their formats, and uses.

Chapters 8 through 13 treat the analysis of spatial data. Chapter 8 focuses on attribute data, attribute tables, database design, and analyses using attribute data. Attributes are half our spatial data, and a clear understanding of how we structure and use them is key to effective spatial reasoning. Chapters 9, 10, 11, and 12 describe basic spatial analyses, including adjacency, inclusion, overlay, and data combination for the main data models used in GIS. They also describe more complex spatio-temporal models. Chapter 13 describes various methods for spatial prediction and interpolation. We typically find it impractical or inefficient to collect "wall-to-wall" spatial and attribute data. Spatial prediction allows us to extend our sampling and provide information for unsampled locations. Chapter 14 describes how we assess and document spatial data quality, while Chapter 15 provides some musings on current conditions and future trends.

We give preference to the International System of Units (SI) throughout this book. The SI system is adopted by most of the world, and is used to specify distances and locations in the most common global coordinate systems and by most spatial data collection devices. However, some English units are culturally embedded, for example, the survey foot, or 640 acres to a Public Land Survey Section, and so these are not converted. Because a large portion of the target audience for this book is in the United States, English units of measure often supplement SI units.

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Exercises

1.1 - Why are we more interested in spatial data today than 100 years ago?

1.2 - You have probably collected, analyzed, or communicated spatial data in one way or another during the past month. Describe each of these steps for a specific application you have used or observed.

1.3 - How are GIS hardware different from most other hardware?

1.4 - Describe the ways in which GIS software are different from other computer software.

1.5 - What are the limitations of using a GIS? Under what conditions might the technology hinder problem solving, rather than help?

1.6 - Are paper maps and paper data sheets a GIS? Why or why not?