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 3000 years (Figure 1-1). Maps are among the most beautiful and useful documents of human civilization.

Most often our geographic knowledge is applied to routine tasks, such as puzzling a route in an unfamiliar town or searching for the nearest diner. Spatial information has a greater impact on our lives than we realize by helping us produce the food we eat, the energy we burn, the clothes we wear, and the diversions we enjoy.

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 treatment of spatial data has accelerated over the past three decades, and continues to evolve.

Key to all definitions of a GIS are “where” and “what.” GIS and spatial analyses are concerned with the absolute and relative location of features (the “where”), as well as the properties and attributes of those features (the “what”). The locations of important spatial objects such as rivers and streams may be recorded, and also their size, flow rate, or water quality. Indeed, these attributes often depend on the spatial arrangement of important features, such as land use above or adjacent to streams. A GIS aids in the analysis and display of these spatial relationships.

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.

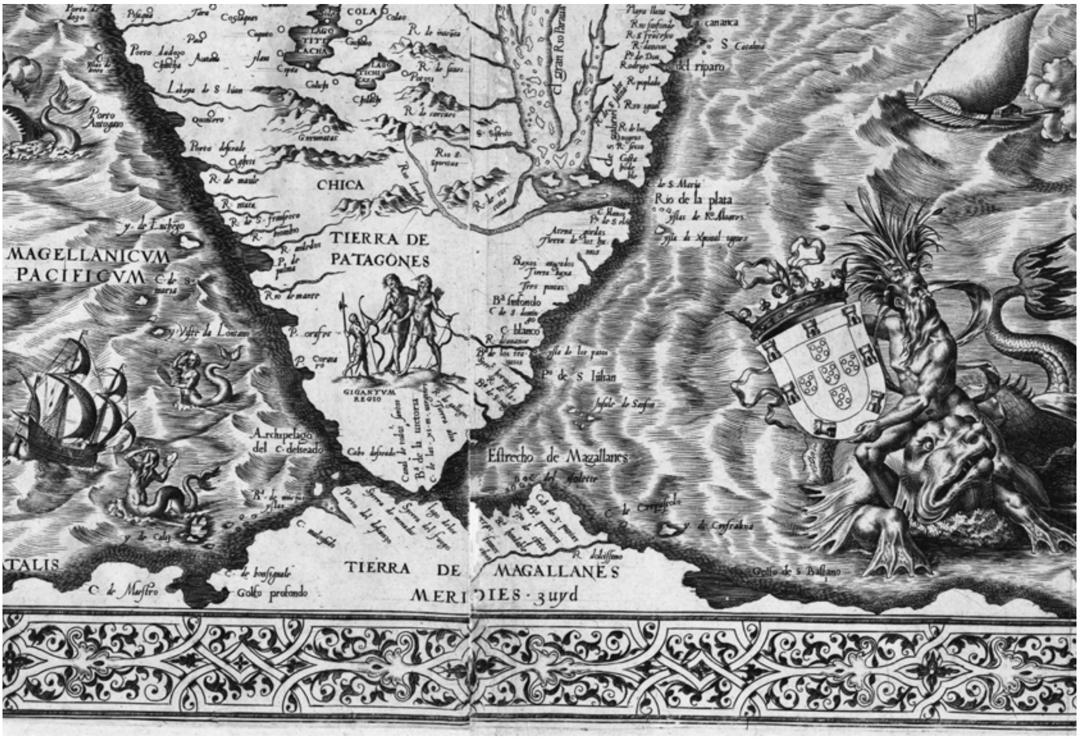

Figure 1-1: A map of southern South America, published 1562 by Diego Gutierrez. The Straits of Magellan are near the lower center, and the Parana River near top center. Early maps were key to exploration.

GIS and spatial analyses are concerned with the quantitative location of important features, as well as 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.

Each GIS user may decide what features are important, and what attributes are worth recording. For example, forests are important to us. They protect our water supplies, yield wood, harbor wildlife, and provide space to recreate (Figure 1-2). We are concerned about the level of harvest, the adjacent land use, pollution from nearby industries, or when and where forests burn. Informed management requires at a minimum 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 relationships and interactions. A GIS is also particularly useful at displaying spatial data and reporting the results of spatial analysis. In many instances GIS is the only way to solve spatially-related problems.

GIS: A Ubiquitous Tool

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.

Why Do We Need GIS?

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 6 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 the earth's surface. The atmosphere and

Figure 1-2: GIS allow us to analyze the relative spatial location of important geographic features. The satellite image at the center shows a forested area in western Oregon, United States, with a patchwork of lakes (dark area, upper left and middle right), forest and clearings (middle), and mountains and desert (right). Spatial analyses in a GIS may aid in ensuring sustainable recreation, timber harvest, environmental protection, and other benefits from this and other globally important regions (courtesy NASA).

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 (Figure 1-4). 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 1-5).

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 1-6), 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.

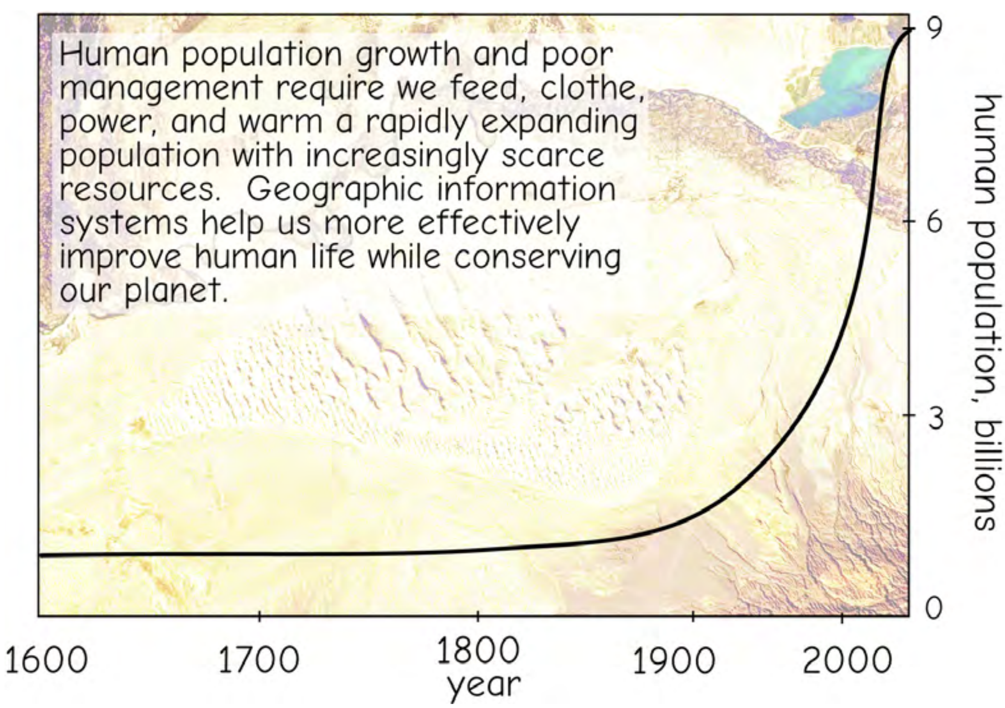

Figure 1-3: Human population growth during the past 400 years has increased the need for efficient resource use (courtesy United Nations and Ikonos).

Figure 1-4: The Sarychev volcano, in the Kuril Islands of Russia, erupted in June, 2009. Advanced satellite imaging allows us to track the eruptions and plumes, new space-based surveying aids in planning evacuation and mapping damage, and repeated observation allows us to overlay observations, measure impacts, and plan for recovery (courtesy NASA).

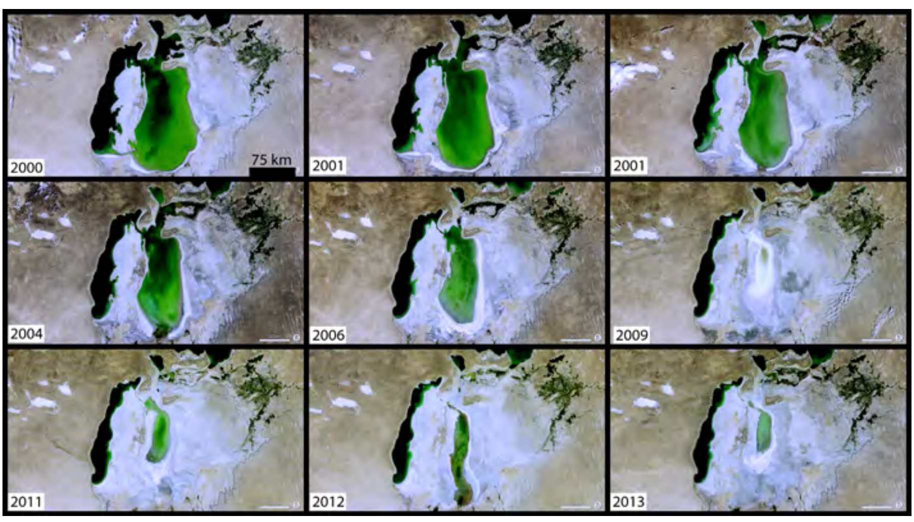

Figure 1-5: The environmental impacts wrought by humans have accelerated in many parts of the world during the past century. These satellite images from 2000 (upper left) to 2013 (lower right) show a shrunken Aral Sea due to the overuse of water. Diversion for irrigation has destroyed a rich fishery, the economic base for many seaside communities. GIS may be used to document change, mitigate damage, and effectively manage our natural resources (courtesy NASA).

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.

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 to today, when anyone can quickly locate their outdoor position to within a few meters. A remarkable positioning technology, generically known as Global Navigation Satellite Systems (GNSS), is now incorporated into cars, planes, boats, and trucks. GNSS are 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 becom-

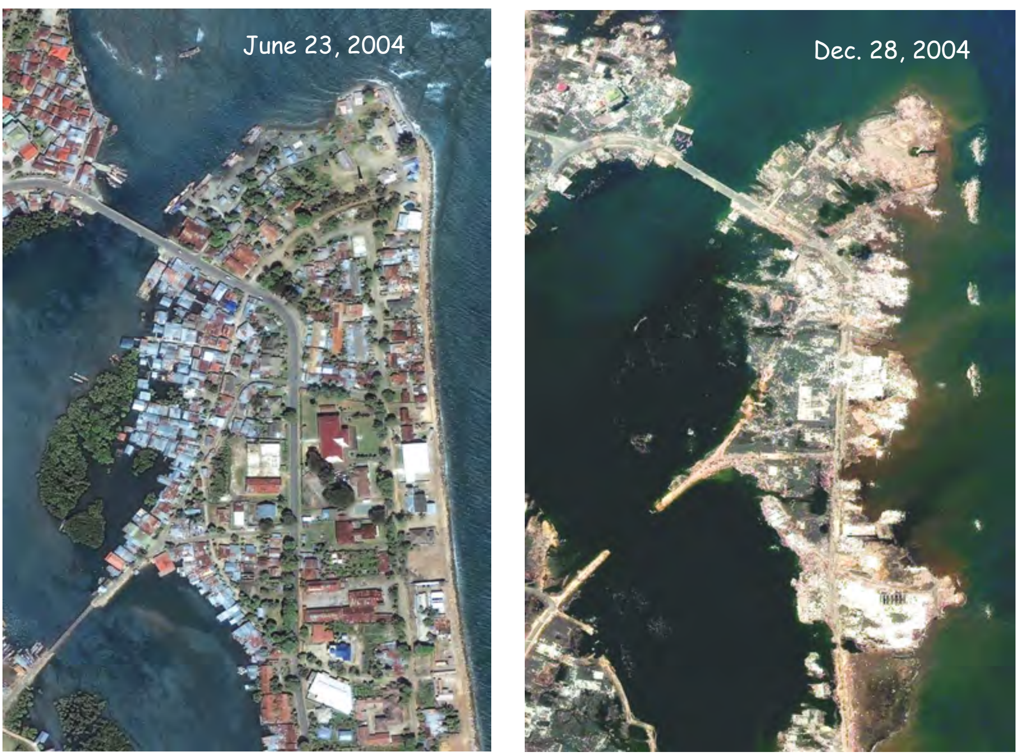

Figure 1-6: GIS may aid in disaster assessment and recovery. These satellite images from Banda Aceh, Indonesia, illustrate tsunami-caused damage to a shoreline community. Emergency response and longer-term rebuilding efforts may be improved by spatial data collection and analysis (courtesy DigitalGlobe).

Figure 1-7: Portable computing is one example of the technological pull driving GIS adoption. (courtesy Cogent3D, www.GISRoam.com).

ing 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 1-7). 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 1-8). Many techniques have been developed for extracting information from image data, and 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.

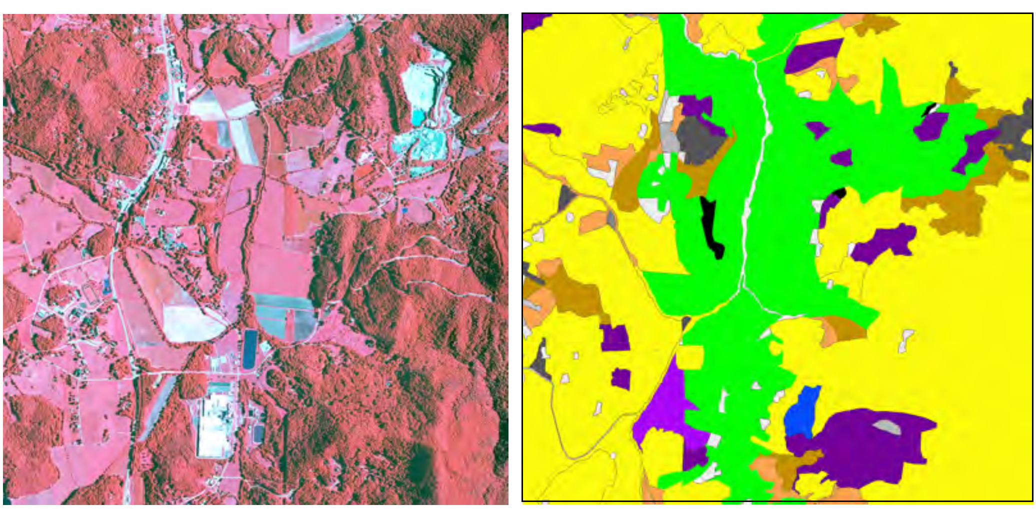

Figure 1-8: Images taken from aircraft and satellites (left) provide a rich source of data, which may be interpreted and converted to information about the earth's surface (right).

GIS in Action

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

Marvin Matsumota 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 1-9).

The search and rescue operation for Mr. Matsumota 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.

GIS are also widely used in planning and environmental protection. Oneida

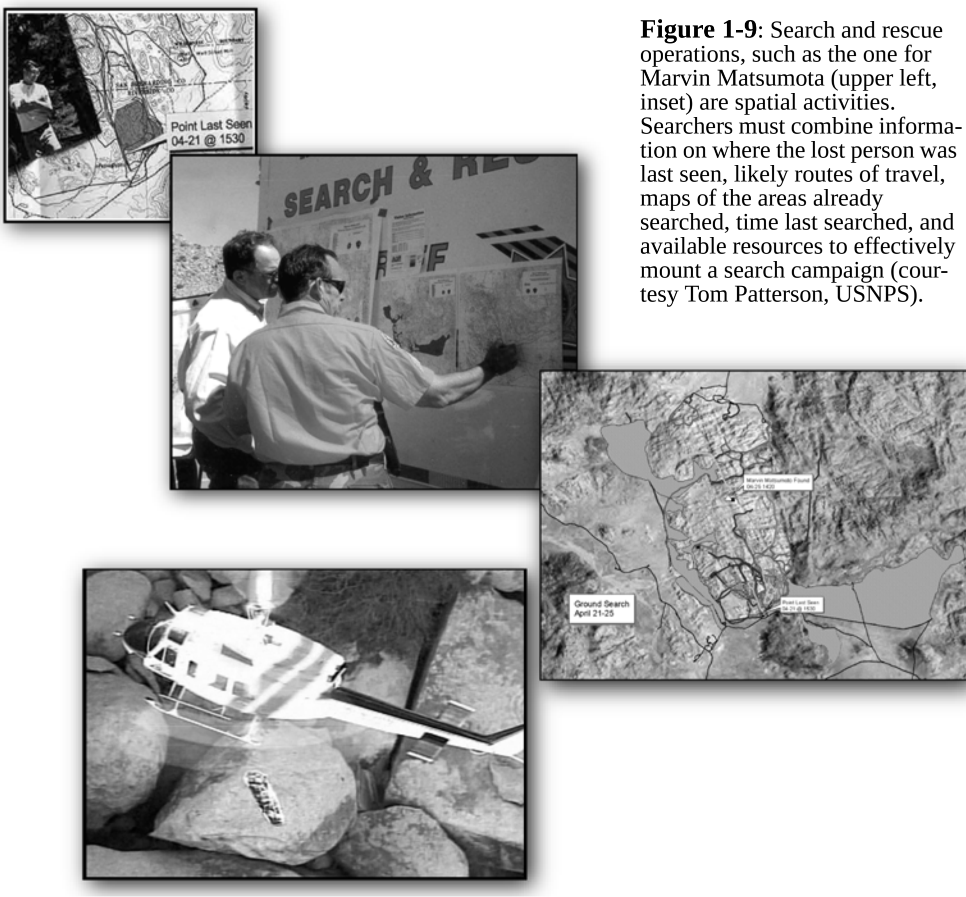

Figure 1-9: Search and rescue operations, such as the one for Marvin Matsumoto (upper left, inset) are spatial activities. Searchers must combine information on where the lost person was last seen, likely routes of travel, maps of the areas already searched, time last searched, and available resources to effectively mount a search campaign (courtesy Tom Patterson, USNPS).

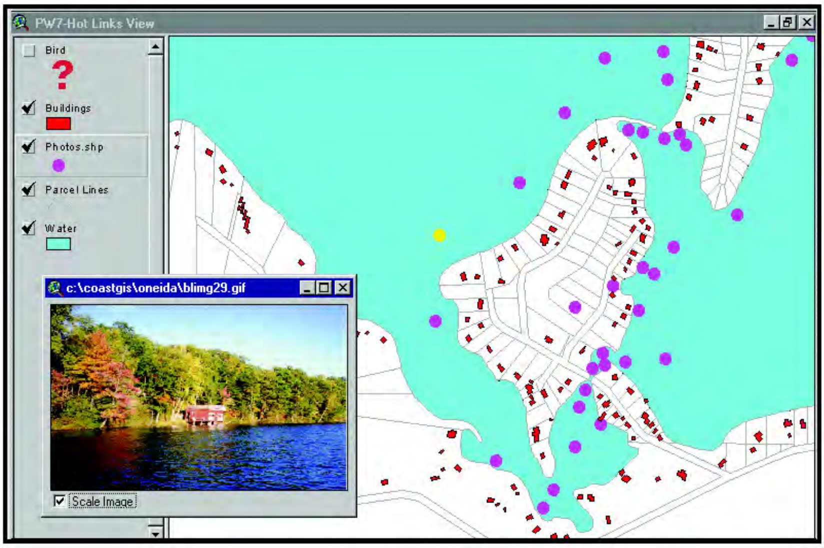

Figure 1-10: Parcel information entered in a GIS may substantially improve government services. Here, images of the shoreline taken from lake vantage points are combined with digital maps of the shoreline, buildings, and parcel boundaries. The image in the lower left was obtained from the location shown as a light dot near the center of the figure (courtesy Wisconsin Sea Grant and LICGF).

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 1-10).

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-

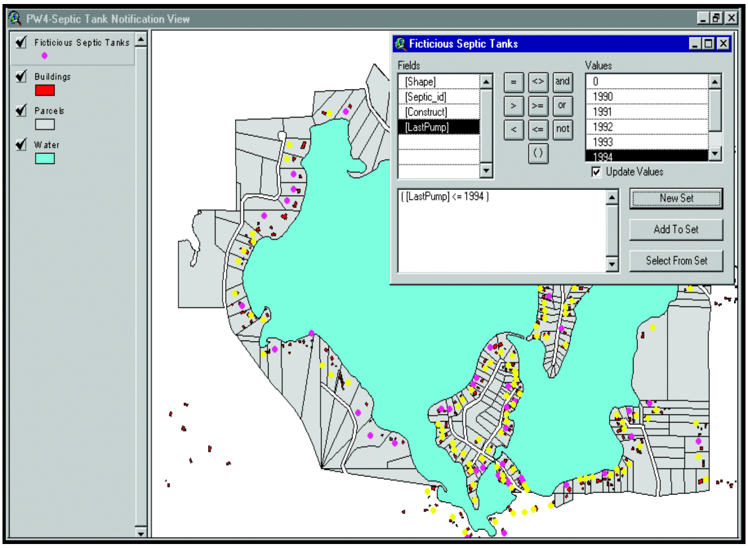

Figure 1-11: GIS may be used to streamline government function. Here, septic systems not compliant with pollution prevention ordinances are identified by white circles (courtesy Wisconsin Sea Grant Institute and LICGF).

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 1-11). Timely maintenance of each septic system must be verified. The GIS can automatically identify owners out of compliance and generate an appropriate notification.

Our third example illustrates how GIS helps save endangered species. The blackfooted ferret is a small carnivore of western North America, and is one of the most endangered mammals on the continent (Figure 1-12). The ferret lives in close association with prairie dogs, communally living rodents once found over much of North America. Ferrets feed on prairie dogs and live in their burrows, and prairie dog colonies provide refuge from coyotes and other larger carnivores that prey on the ferret. The blackfooted ferret has become endangered because of declines in the range and number of prairie dog colonies, coupled with ferret sensitivity to canine distemper and other diseases.

The U.S. Fish and Wildlife Service (USFWS) has been charged with preventing the extinction of the blackfooted ferret. This entails establishing the number and location of surviving animals, identifying the habitat requirements for a sustainable population, and analyzing what factors are responsible for the decline in ferret numbers, so that a recovery plan may be devised.

Because blackfooted ferrets are nocturnal animals that spend much of their time underground, and because ferrets have always been rare, relatively little was known about their life history, habitat requirements, and the causes of mortality. For example, young ferrets often disperse from their natal prairie dog colonies in search of their own territories. Dispersal is good when it leads to an expansion of the species. However, there are limits on how far a ferret may successfully travel. If the nearest suitable colony is too far away, the dispersing young ferret may likely die of starvation or be eaten by a larger predator. The dispersing ferret may reach a prairie dog colony that is too small to support it. Ferret recovery has been hampered because we don't know when prairie dog colonies are too far apart, or if a colony is too small to support a breeding pair of ferrets. Because of this lack of spatial knowledge, wildlife managers have had difficulty selecting among activities that might improve ferret survival. These include the establishment of new prairie dog colonies, fencing colonies to prevent the entry of larger predators, removing predators, captive breeding, and the capture and transport of young or dispersing animals.

GIS have been used to help save the blackfooted ferret (Figure 1-12). Individual ferrets are tracked in nighttime spotlighting surveys, often in combination with radio-tracking. Ferret location and movement are combined with detailed data on prairie dog colony boundaries, burrow locations, surrounding vegetation, and other spatial data (Figure 1-13). Individual ferrets can be identified and vital characteristics monitored, including home range size, typical distance traveled, number of offspring, and survival. These data are combined and analyzed in a GIS to improve the likelihood of species recovery.

Figure 1-12: Specialized equipment is used to collect spatial data. Here a burrow location is recorded using a GPS receiver, as an interested black footed ferret looks on (courtesy Randy Matchett, USFWS).

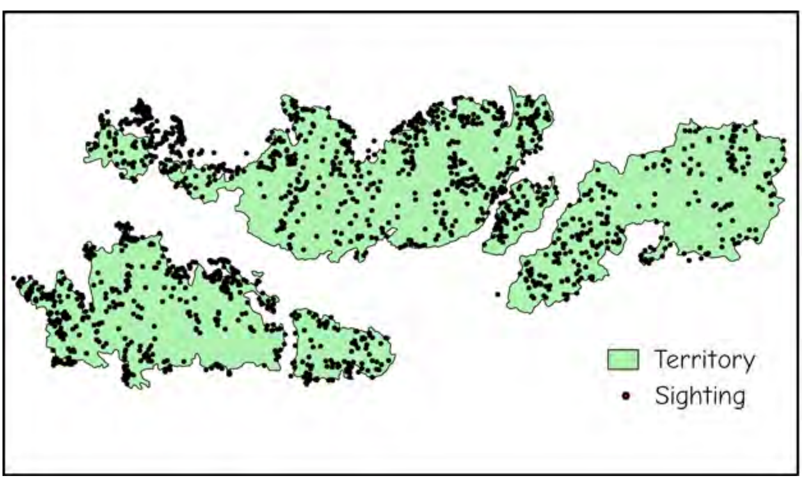

Figure 1-13: Spatial data, such as the boundaries of prairie dog colonies (gray polygons) and individual blackfooted ferret positions (triangle and circle symbols) may be combined to help understand how best to save the blackfooted ferret (courtesy Randy Matchett, USFWS).

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 wood combustion (Figure 1-14). Air pollutions shaves 10 years off of the life span of about 200,000 people in the United States each year. It also causes increased sickness, hospitalization, and medical costs that annually reach into the billions of dollars. Decreasing air pollution concentrations has been shown to significantly increase life expectancy (Figure 1-15, bottom).

Reducing sickness and death requires identifying areas of high exposure, particularly for vulnerable populations. Effective management requires 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 over both 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 1-15, 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 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 1-15), 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.

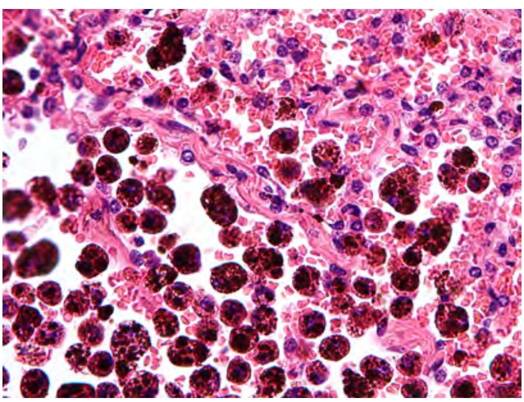

Figure 1-14: Small particles lodge in the lungs, cause inflammation and reducing lung function. Alveolar macrophages attempt to isolate this material, but air pollution levels commonly exceed the lung's capacity for self-cleaning. Excessive exposure often shows as concentrations of dark particles on lung micrographs, as seen above. Damaging particle concentrations are typically higher in urban areas, or near traffic, power plants, and other pollution sources. Pollutants may be concentrated due to weather, time of day, and local and regional topography. GIS has been used to map concentrations, identify sources, and plan improvements (courtesy Nephron).

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 estimate an average 2-year increase in life span for each 10 $\mu g\text{-}m^{-3}$ reduction in exposure (Figure 1-15, 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 con-

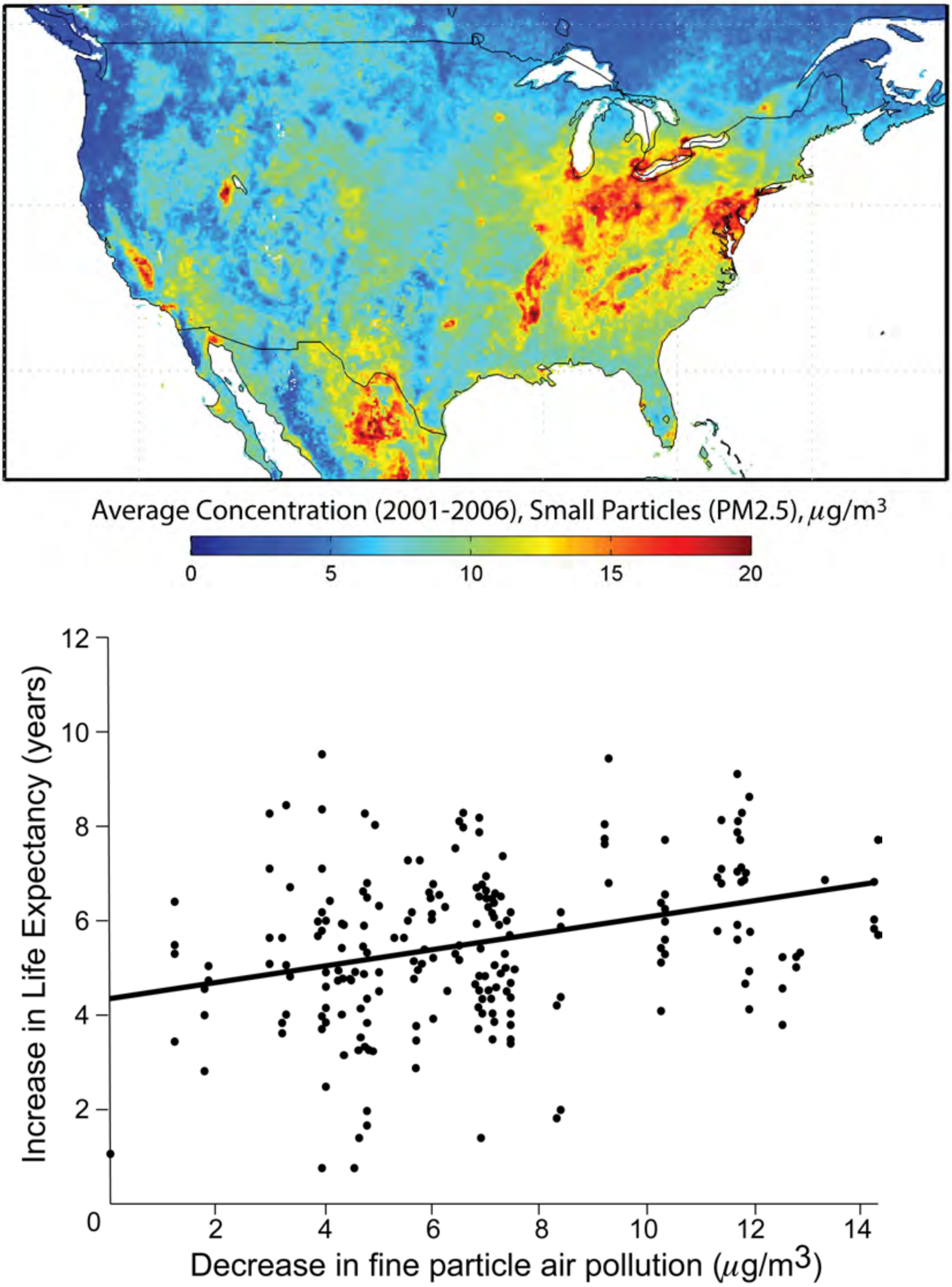

Figure 1-15: Scientists at NASA have developed methods to map air pollution across continents on a daily basis, which may be averaged to estimate chronic exposure (top). These spatial data may be combined with studies on human response to air pollution (bottom) and the location of vulnerable populations to improve public health and reduce medical costs.

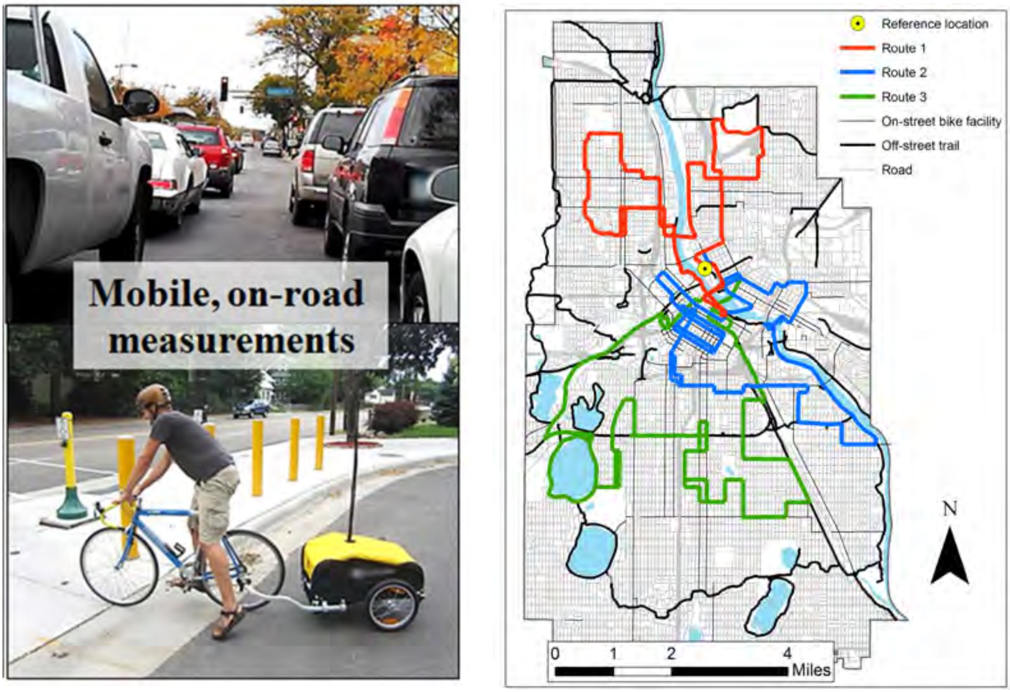

Figure 1-16: Towable samplers help measure air pollution for individual streets, at various traffic densities and types (courtesy J. Marshall).

centrations at very fine spatial intervals, towing an air sampling system behind a bicycle through a range of traffic densities, road types, and neighborhoods (Figure 1-16). Satellite positioning was synchronized with video and air samples, and these combined 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 1-17). 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.

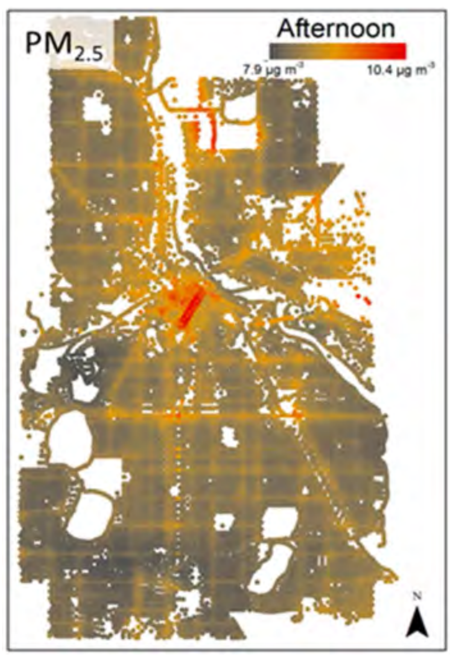

Figure 1-17: Fine-detailed spatial estimates of particulate air pollutants (courtesy J. Marshall).