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Remote Sensing and Geographic Information Systems: Technologies for Mapping and Monitoring Environmental Health

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> The face of our land looks to the sky. To see its many features,
> we must get above it and look down.
>
> *(Dill 1958)*

Henry Dill's statement was made in the context of using air photographs to evaluate changes in agricultural land use. Three and a half decades later, his "bird's-eye view" is even more relevant as specialized cameras, electronic scanners, satellites, and computer technology have been added to the arsenal of tools that help us gather, map, and monitor the characteristics of earth resources (Rudd 1974; Harper 1976; Richards 1986; Star 1991). In this chapter, we illustrate how some of these tools, *remote sensing* and *geographic information systems* (GIS), are being used to assist in the rehabilitation of the Sudbury region.

Environmental monitoring is fundamental to the complex task of natural resource management. A well-designed monitoring program should enable (Yan and Keller 1991)

measurement of natural variation in the structure and dynamics of ecosystems
identification of sites with special attributes
exploration of patterns at various scales
detection of changes that are gradual or cyclic in nature
recognition and evaluation of unusual events
improved capability to predict the ecological outcome of future events

But monitoring is neither a simple nor an inexpensive endeavor, especially of processes such as the acidification and recovery of the Sudbury region, which affect large areas over long periods of time. It is here that remote sensing and GIS have a unique and important role to play.

Remote sensors, especially satellite sensors, produce images that cover large areas for a few cents per square kilometer, and most important, the same coverage is repeated month after month. If information relevant to the monitoring program can be extracted from these images, then remote sensing can offer a full two-dimensional view that cannot be matched by point sampling. GIS offers other advantages. Developed from computer-assisted cartography, GIS has many tools designed to produce maps from point data, to analyze existing maps, and to explore the spatial patterns within and between maps. Moreover, GIS enables us to combine and transform useful but static maps into dynamic scenarios of our resources. In combination, GIS and remote sensing complement and enrich ground-based sampling programs, contributing to the cost-effective achievement of monitoring goals.

Box 23.1. Landsat 6 Disaster!!

In the fall of 1993, remote sensing scientists throughout the world were shocked to hear the news that the $200 million (US) Landsat 6 had failed to reach orbit after launch and probably plunged to the ocean. Many had been counting on this satellite, which included new instrumentation, to supply applications data until the year 2000. Fortunately, satellite data for resources monitoring continues to be received from Landsat 5 as well as French, joint European, Russian, Indian, and Japanese satellite programs. As well, Canada's RADARSAT program is expected to be fully operational by 1995 and promises to provide all-weather coverage of exceptional value for geology, oceanography, sea-ice monitoring, flood monitoring, agriculture, and forestry.

Remote Sensing

Remote sensing is the measurement or acquisition of information by a recording device that is not in physical contact with the object under study. This includes computer or digital images taken from satellites, photographs taken from airplanes, and color measurements taken with hand-held sensors. In the Sudbury region, several remote sensing studies have been carried out, most of which have used digital images taken from sensors mounted on the Landsat series of satellites.

Since the Landsat program began in 1972, there have been five Landsat satellites (Box 23.1). All five carried a recording instrument called the multispectral scanner (MSS). An improved scanner, the thematic mapper (TM), was added to the last two satellites (Landsat 4 1982; Landsat 5 1984). These instruments measure the earth's reflected radiation in specific and relatively narrow bands of the electromagnetic spectrum (Table 23.1). Also, TM is capable of sensing emitted or thermal radiation from the earth.

The Landsat sensors collect continuous readings over a 185-km-wide swath along the orbital track of the satellites. The smallest area on the ground for which measurements can be made is called a pixel, short for "picture element." An MSS pixel covers an area that is 79 m by 79 m, slightly larger than 0.6 h. For TM, the pixel size is 30 m by 30 m (0.1 ha). Each image is made up of a set of four (MSS) or seven (TM) bands, with each band composed of a grid of several million pixels.

In theory, every spot on earth is imaged at 16–18-day intervals, although this varies depending on the satellites in operation and cloud cover. The repetitive coverage is considered to be one of the great advantages of satellite resource monitoring.

The key to interpreting remotely sensed data is held in the concept that earth materials reflect the sun's radiation differently, making

TABLE 23.1. Landsat Spectral Bandwidths for the Multispectral and Thematic Mapper Scanners

Multispectral scanner (Landsat 1, 2, 3, 4, 5)		Thematic mapper (Landsat 4, 5)	
Band no.	Channel wavelengths[a]	Band no.	Channel wavelengths[a]
1	0.5–0.6 (green/yellow)	1	0.45–0.52 (blue)
2	0.6–0.7 (red)	2	0.52–0.60 (green/yellow)
3	0.7–0.8 (near-infrared)	3	0.63–0.69 (red)
4	0.8–1.1 (near-infrared)	4	0.76–0.90 (near infrared)
		5	1.55–1.75 (mid-infrared)
		6	10.4–12.5 (thermal IR)
		7	2.08–2.35 (mid-infrared)

[a] Wavelength bounds expressed in µm.

each appear in unique but typical colors. Thus, materials are said to have a characteristic spectral signature or spectral response pattern (Swain and Davis 1978; Richards 1986; Campbell 1987). In reality, different materials may sometimes look alike, or the same material may display a range of spectral responses. However, the spectral response measured by a satellite sensor usually can be interpreted in terms of the materials being viewed. For example, deep clear water is most reflective in the blue wavelengths, but as sediment is added to the water, the peak response shifts to the green. Vegetation, which humans see as green, in fact is most reflective in the near-infrared (NIR), and any decrease at this wavelength is usually interpreted as a sign of plant stress.

Remote Sensing Applications

Sudbury Vegetation Surveys

The damaged area surrounding Sudbury is of sufficient size that satellite imagery provides the only convenient and affordable means of monitoring it. One of the earliest studies was undertaken using MSS imagery, with the goal of mapping zones of anthropogenic influence in the Sudbury region (Pitblado and Amiro 1982). This project accompanied an extensive field program (Amiro and Courtin 1981) in which many vegetation plots were described to provide baseline data for future vegetation monitoring.

For this study, a map of the vegetation index (*VI*) was prepared from a late-summer MSS image using the second MSS NIR band (band 4) and the red (band 2).

$$VI = \frac{NIR - Red}{NIR + Red}$$

Vegetation indices (of which VI is but one version) have long been reported in the remote sensing literature (Tucker 1979). These indices are highly correlated with the density of vegetation canopy cover, biomass, leaf area, and certain seasonal vegetation characteristics. Dense vigorous vegetation gives high VI values because of its strong NIR reflection. Water, bare soil or rock, clouds, and shadows give low VI values because these materials reflect almost equally at red and NIR wavelengths.

For the image analyzed, the lowest VI values were centered around the smelter sites where the ground was barren or only a few stunted trees survived, and progressively higher VI values were found with distance from the smelters. Two such maps are shown in Figure 23.1 (1973) and Figure 23.2 (1986). The unvegetated runways of the Sudbury airport show as a dark gray cross just south of Wanapitei Lake. Dark gray barren areas surround the Falconbridge smelting complex near the airport, the Coniston smelter (closed in 1972) east of Ramsey Lake, and the Copper Cliff smelting complex west of Ramsey Lake along the left edge of the image.

A simple visual comparison of these two maps shows that the vegetation has increased dramatically over the 1973–1986 period (i.e., far less-dark, low biomass areas in 1986). Research is currently in progress to quantify the changes by revisiting the original field sites (Winterhalder and Sinclair, *personal communication*) and relating actual biomass to the MSS-derived VI (Courtin and Beckett, *personal communication*). These efforts will enable us to provide quantitative estimates of change over the entire region and to monitor the spatial patterns of change. Without remote sensing, such analyses would be impossible at the scale required.

Vegetation change mapping has also been undertaken by Inco Limited to monitor the effects of emission reductions and reclamation efforts (Allum and Dreisinger 1986). The method used allows only qualitative estimates of vegetation change. In this example, change was recorded for periods as short as 3 years. The company concluded that Landsat imagery provides a cost-effective and reliable means of monitoring vegetation change over large areas.

Lake Water Quality Surveys

Lake water sampling is expensive, especially of many lakes scattered over a large area with limited accessibility. Remote sensing has the capability to measure at least some surface water parameters and thus can be used to extend and complement traditional sampling

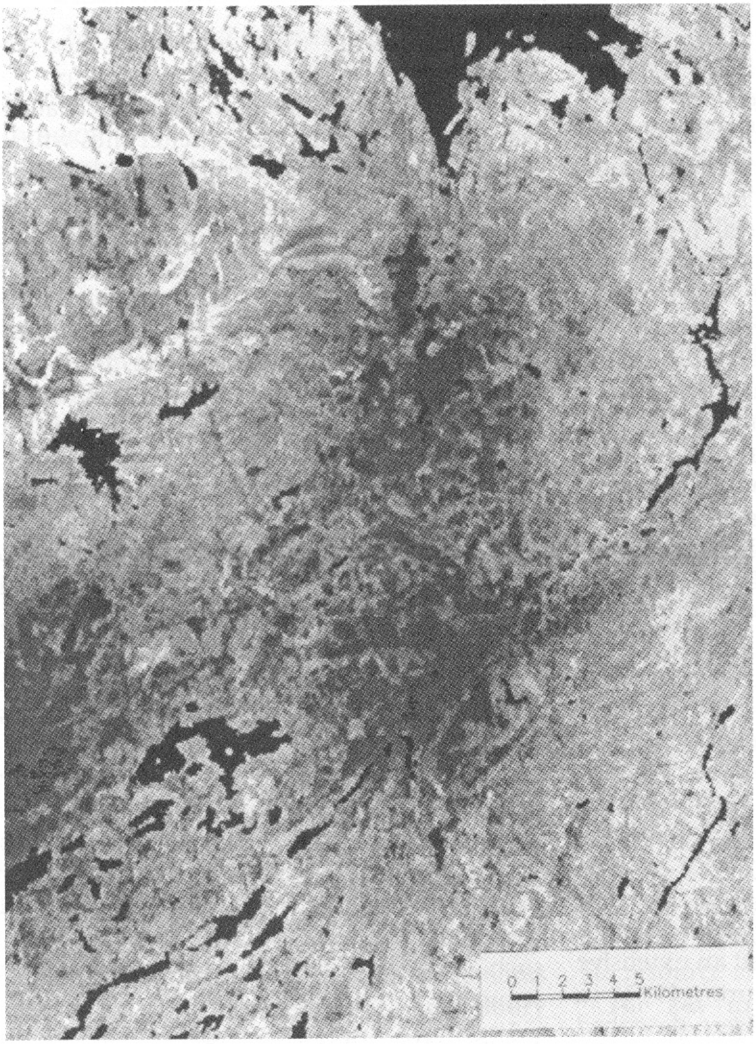


FIGURE 23.1. Relative biomass (vegetation index) image derived from a Landsat 1 multispectral scanner scene taken July 13, 1973. Wanapitei Lake is located at the top center of the image. Ramsey Lake is one-third up from the bottom and one-quarter in from the left edge of the image. Lighter tones represent higher biomass values.

programs. A few studies have focused on the feasibility of remotely measuring acidity (Hardy and Jefferies 1981; Moniteq 1982). However, only one study has been undertaken in the Sudbury region to map acidic and non-acidic lakes (Pitblado 1992a,b).

In this study, 227 lakes throughout northeastern Ontario (Fig. 23.3) were used to calibrate relationships between Landsat TM radiance measurements and concentrations of dissolved organic carbon (DOC) collected from field surveys. With the exception of bog or marsh waters, acidic lakes have very low DOC concentrations (Yan 1983), possibly due to aluminum, which may cause DOC to precipitate out of the water column (Effler et al. 1985). Because DOC is the dominant coloring agent in northern lakes, acidic lakes are very clear or transparent. In turn, this affects the radiance viewed by satellite sensors, especially blue radiance viewed by TM band 1.

For the 227 lakes, the DOC of 70% of the lakes was predicted within ±1 mg/L, whereas 90% were within ±2 mg/L (Fig. 23.4). This is relevant to mapping pH because of the strong link between pH and DOC for anthropogenically acidified lakes. The pH-DOC relationship is similar, although weaker, when a wider selection of lakes is included. Thus, DOC can be used as a surrogate for mapping pH, especially

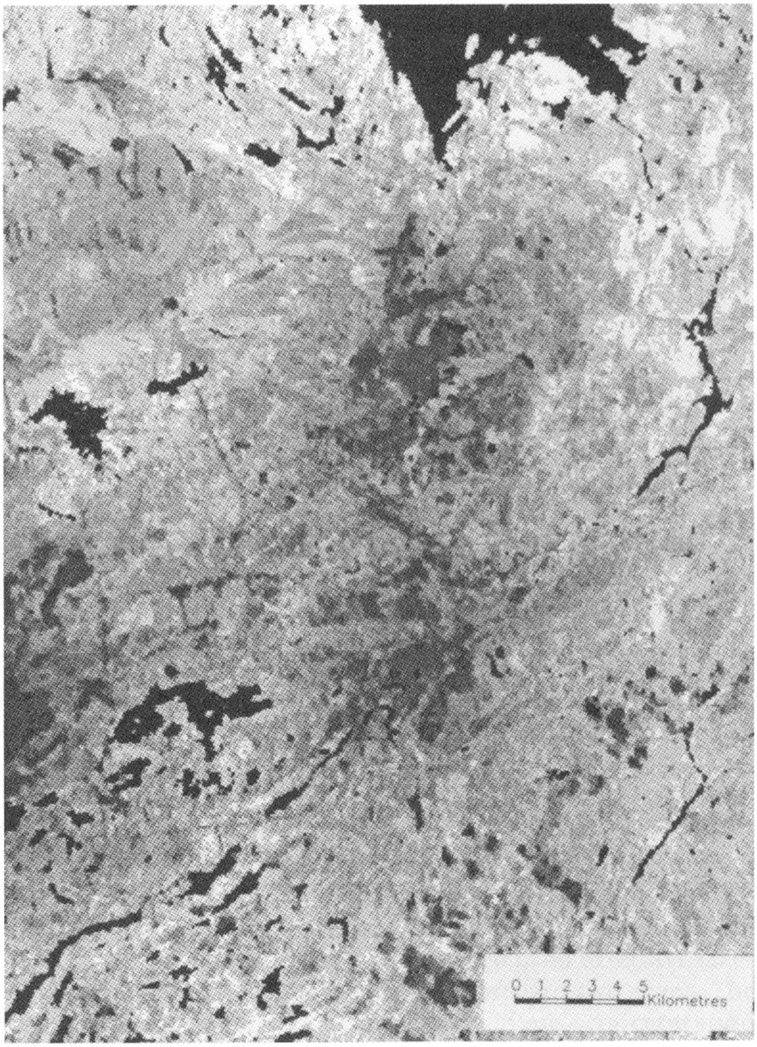


Figure 23.2. Relative biomass (vegetation index) image derived from a Landsat 5 multispectral scanner scene taken August 13, 1986. Vegetation recovery is suggested here by the increase in areas of high biomass values (lighter tones) compared with the 1973 image. Dark patches that look like lakes in the lower right section but that do not appear on the 1973 image are clouds and cloud shadows.

in the greater Sudbury area. When this approach was applied to the lakes north of Wanapitei Lake, every one of the known acidic lakes (pH <5.6) was identified, and it seems reasonable to expect that the other lakes so identified have also been mapped correctly.

To meet the goals of monitoring, however, one must be able to measure whether water quality is changing with time. This is a more challenging problem for remote sensing because differences in the atmosphere between images may mask changes in a lake. Nine images of Bowland Lake (located 70 km north of Sudbury) from 1973 to 1986 were used to look for small changes in DOC due to liming (Pitblado 1992a,b). The images provided tantalizing evidence of an increase, but the data were not statistically significant. The actual change in DOC over the short time period, 1982–1985, was only 0.5 mg/L (Molot et al. 1990), and it would appear that larger differences are required before MSS or TM can detect them.

Geographic Information Systems

Multifaceted and multifunctional, a GIS is a computerized database management system for the capture, storage, retrieval, analysis, and

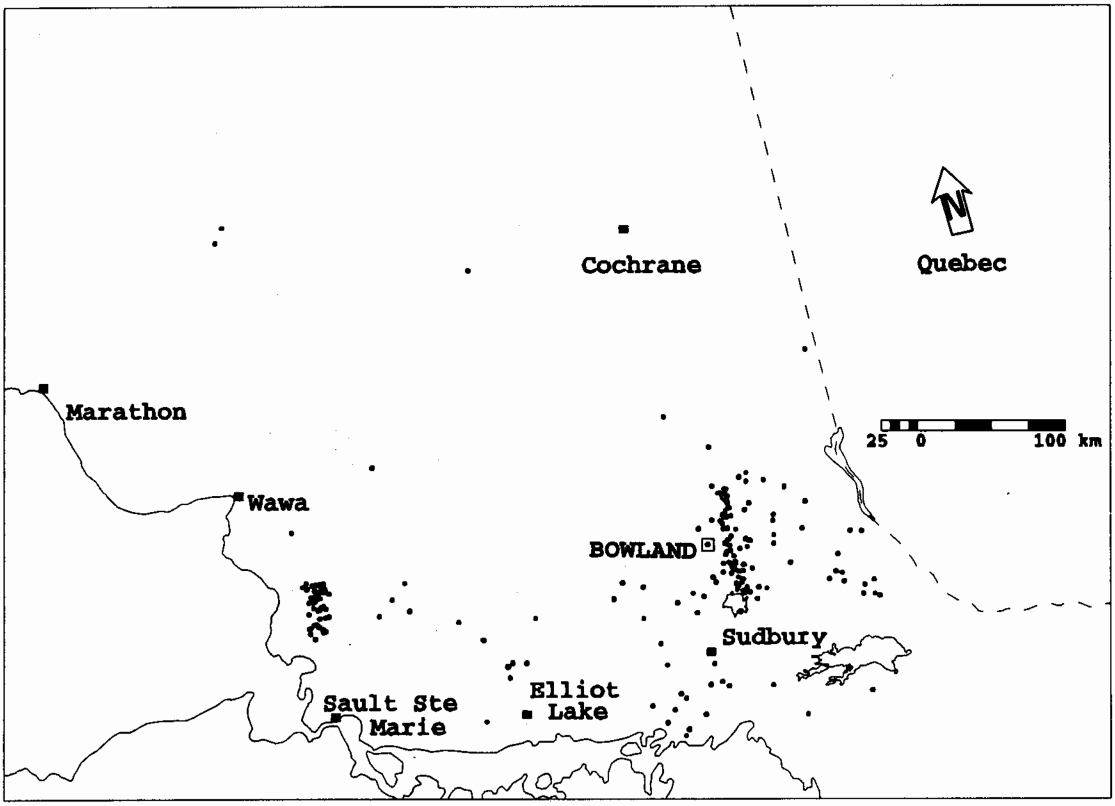


FIGURE 23.3. Location of 227 lakes used to calibrate Landsat thematic mapper radiance measurements and concentrations of dissolved organic carbon. As well, Bowland Lake was used to assess thematic mapper capability of detecting temporal changes in water quality (pre- and postneutralization with lime).

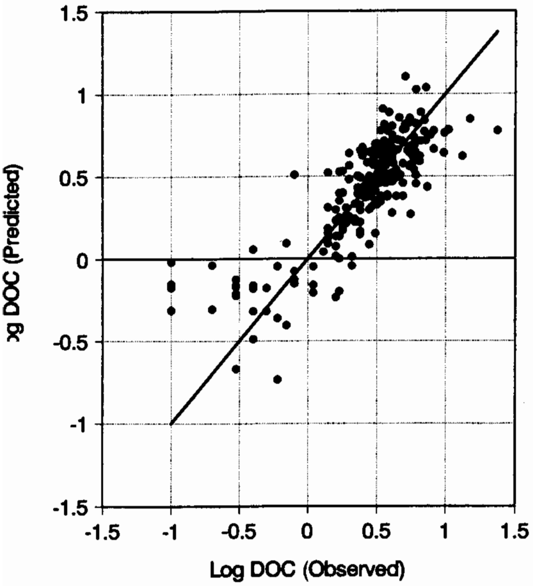


FIGURE 23.4. Highly correlated dissolved organic carbon measurements. Observed measurements (transformed here to logarithms of the original mg/L values) were obtained using traditional field survey techniques, and the predicted measurements were computed using Landsat thematic mapper data.

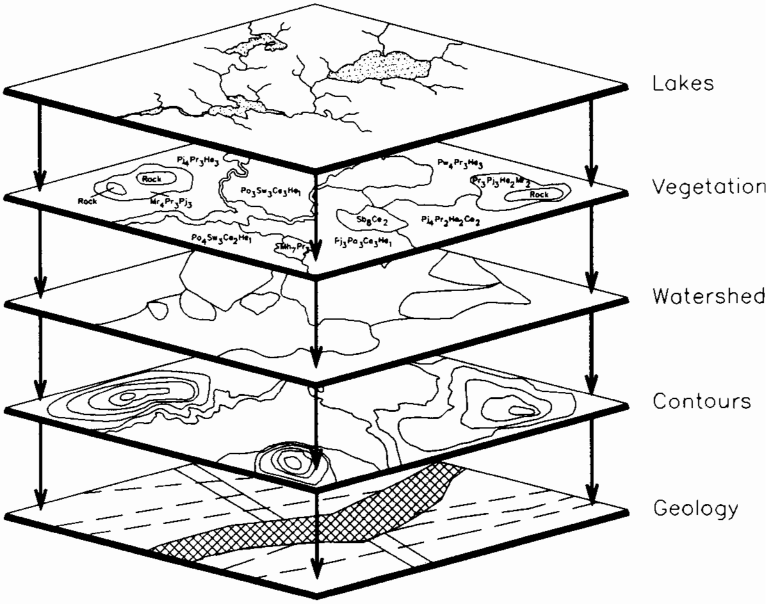


FIGURE 23.5. Schematic representation of thematic layers used in an overlay analysis using a geographic information system.

display of spatial or mapped data (Burrough 1986; Aronoff 1989). Evolving from computer mapping programs written in the 1960s, GIS programs transform paper maps into a digital or computer form, calculate areas, lengths, and perimeters, and facilitate the process of comparing two or more maps using overlay analyses. Thus, the integration of information from several single-discipline maps can be performed more quickly and reproducibly (Fig. 23.5).

The capabilities of GIS programs rapidly progressed beyond simple measurement and overlay techniques, however. Users soon realized that entirely new map layers could be developed from existing information. For instance, the elevation contour data found on topographic maps can be used to create maps of slope and aspect. In turn, these and other GIS parameters can be used in ecological or physical models that lead to a better understanding of ecosystem function or the consequences of land use planning decisions.

GIS Applications

Sudbury Lake Acidification Zone

In many of the previous chapters, a map of the Sudbury lake acidification zone has appeared. This map was created using GIS and illustrates overlay analysis and the capability to create maps from point data stored in a database (Neary et al. 1990; *personal communication*).

Between 1979 and 1988, water chemistry was sampled from more than 2000 lakes in central Ontario by the Ministry of the Environment and the Ministry of Natural Resources. Data were stored in an extensive lakes database and used to prepare two maps. The first is a map of sulfate concentration (Fig. 23.6). The isolines (lines joining points of equal value) were found by applying the value of sulfate concentration from each lake sample station to a circular area (30-km radius) surrounding the station. Where the circles from two or more stations overlapped, the value was based on a weighted average, with the weighting of adjacent points declining exponentially with distance.

The second map was prepared showing the ratio of sulfate concentration to sulfate plus alkalinity. This ratio approaches zero when sulfate concentrations are low or when carbonate-rich rocks maintain high alkalinity and approaches 1.0 when acidification has reduced the alkalinity of lakes (Fig. 23.7).

The zone adversely affected by the Sudbury smelters was defined as the area where sulfate

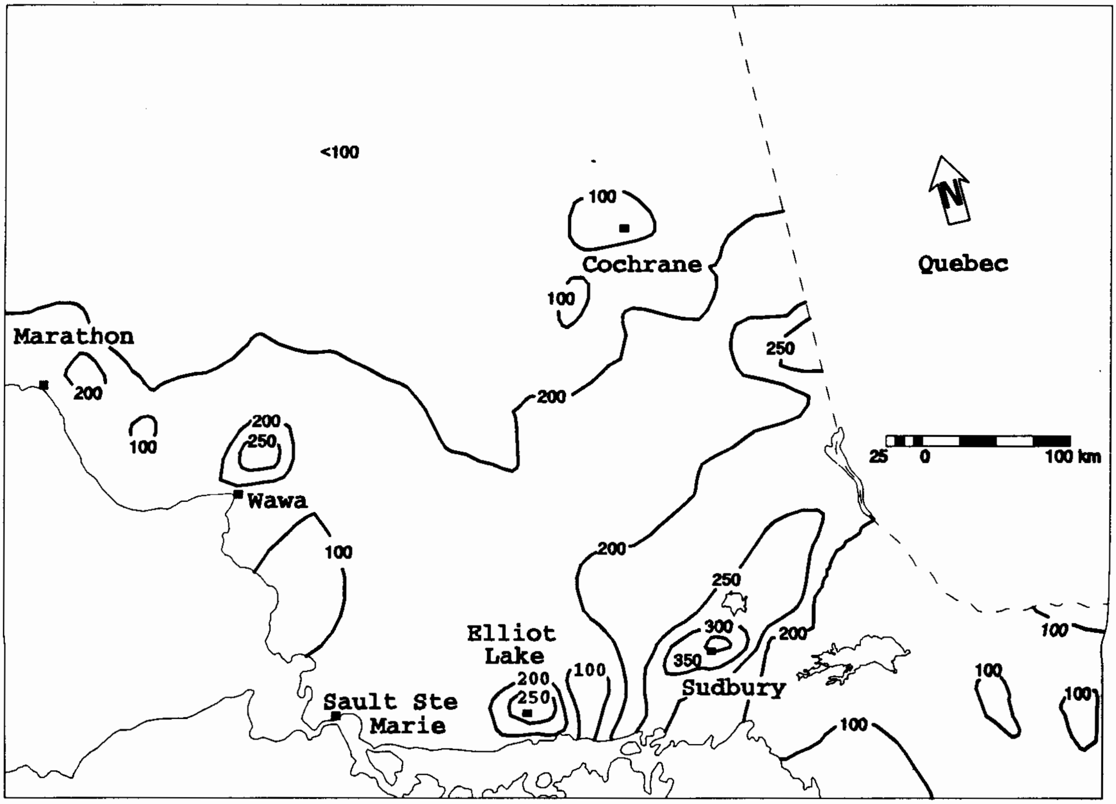


FIGURE 23.6. Lake surface water sulfate concentration. All contour values are in μeq/L SO_4 (from Neary et al. 1990).

concentration exceeded 200 μg/L and the sulfate/(sulfate + alkalinity) ratio exceeded 0.7. The intersection identifies zones affected by local sulfur emissions as opposed to long-range transport of sulfur. The Sudbury Lake Acidification Zone stands out, calculated to cover approximately 17,000 km^2 (Fig. 23.8).

GIS was essential to this study. Traditionally, detailed data have been stored in files or, more recently, in databases. To see how the information varied locally or regionally, either many maps had to be prepared or the information had to be generalized. Because the process of plotting hundreds of points and then contouring them was costly, the spatial variation of data was seldom studied. GIS allows isoline maps to be prepared rapidly and provides new and advantageous techniques for doing so. Also, specialized maps can be produced as required using many combinations of variables in the database.

Daisy Lake Watershed Liming Study

Daisy Lake is a metal-contaminated acidified lake (pH 4.9) about 3 km from the former Coniston smelting complex. Two small subwatersheds have been intensively studied for several years in preparation for a watershed liming experiment. GIS has helped with the visualization and understanding of the data. For example, soil pH, mapped from point samples, shows a distinct spatial pattern (see Plate 14 following page 182). Low pH values in the northeast are easy to explain because this area is closest to the former smelter. The reason for the remaining pattern becomes clear when the pH map is draped over the topography. Low pH is found on exposed slopes facing the Coniston complex, slopes that

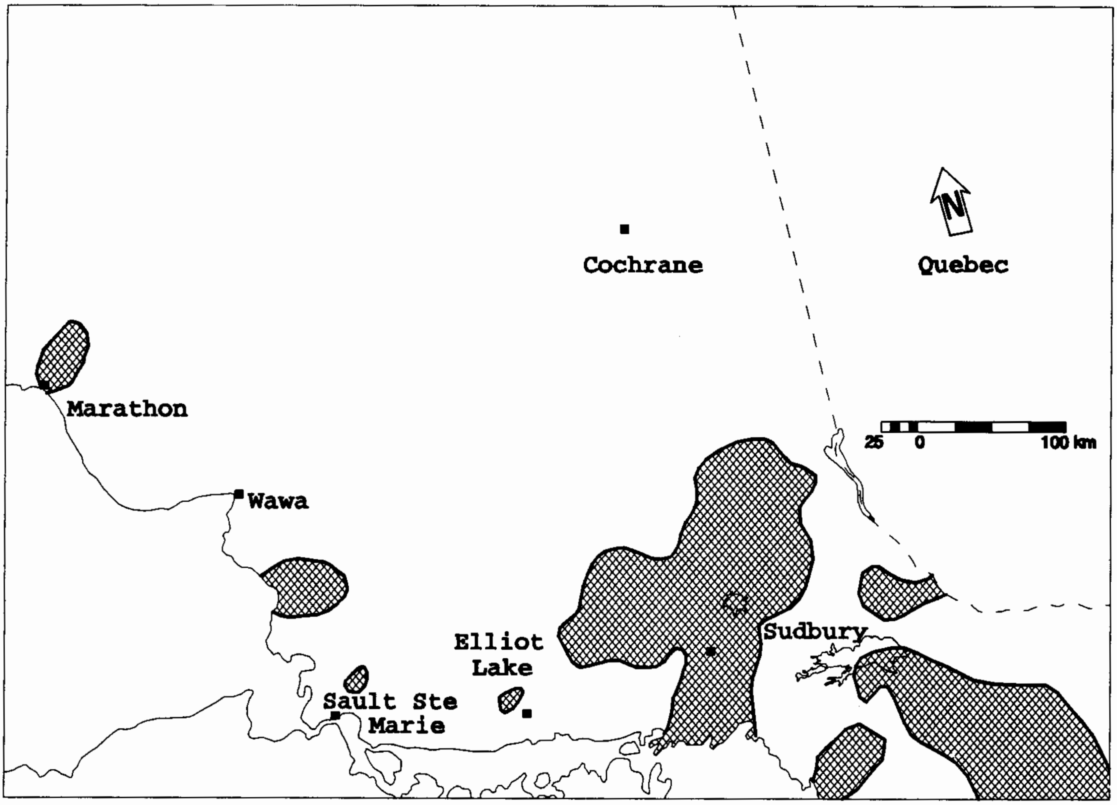


Figure 23.7. Zones where lakes have sulfate/(sulfate+alkalinity) ratios greater than 0.7. The zone around Sudbury is primarily due to local smelter effects. The other zones are probably due to long-range transport of sulfur compounds (from Neary et al. 1990).

were fumigated by clouds of sulphur gases drifting down the Daisy Lake valley. Highest pH is found in areas most protected from northeast winds (see Plate 17 following page 182).

Remote Sensing and GIS Integration

In the remote sensing examples discussed earlier, analyses were undertaken without the help of GIS. Similarly, in the GIS applications, all the information was derived from ground surveys. As the two fields mature, the common spatial view of the world that they share has lead to increasing fusion of the technologies.

Counts and Measures

For small-scale (large area) investigations, an excellent example of remote sensing/GIS integration is the work recently completed by Hélie et al. (1993). Using 129 Landsat TM scenes for most of eastern Canada (south of 52° north latitude from the Manitoba-Ontario border to the Atlantic provinces), 881,634 water bodies were counted and measured in terms of size. GIS facilities enabled the researchers to associate these water bodies with major drainage basins and with digitized maps of ecodistricts interpreted as areas having a low, moderate, or high potential to reduce acidity (see Chapter 1). Seventy-three percent of these water bodies were found to lie in areas having low potential.

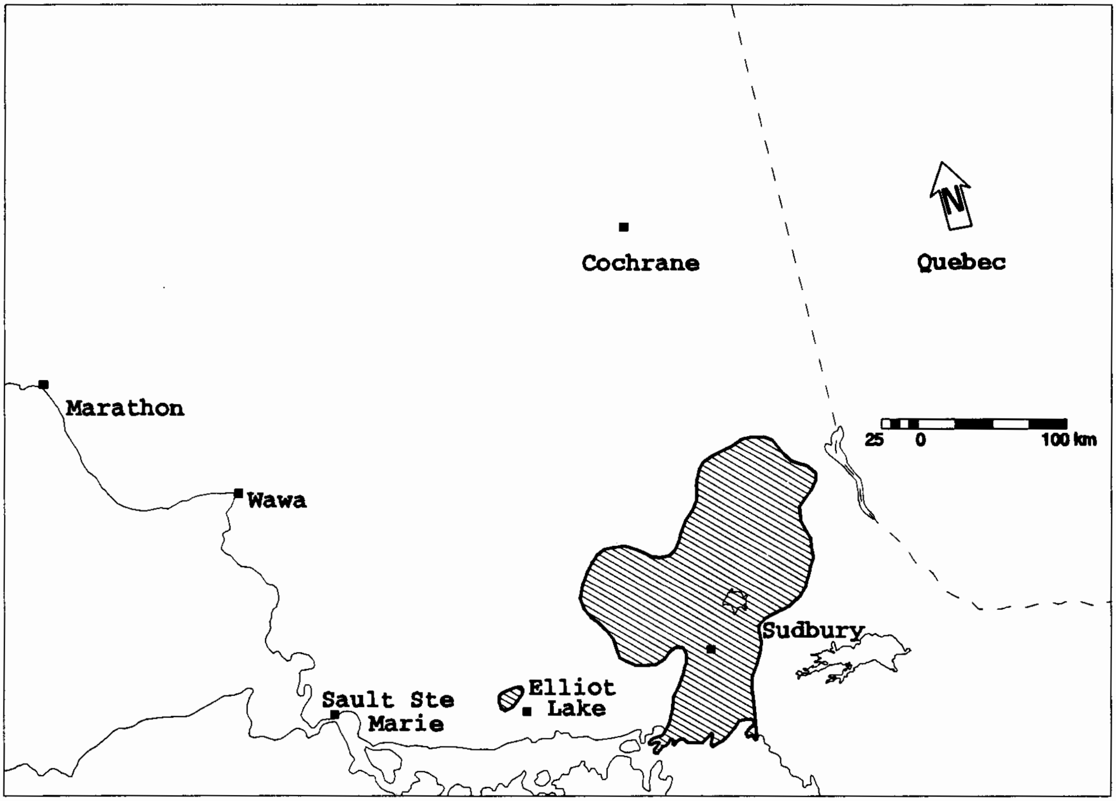


FIGURE 23.8. Lake acidification zones. The small area near Elliot Lake is based on data from very few lakes and may be altered with more lake data (from Neary et al. 1990).

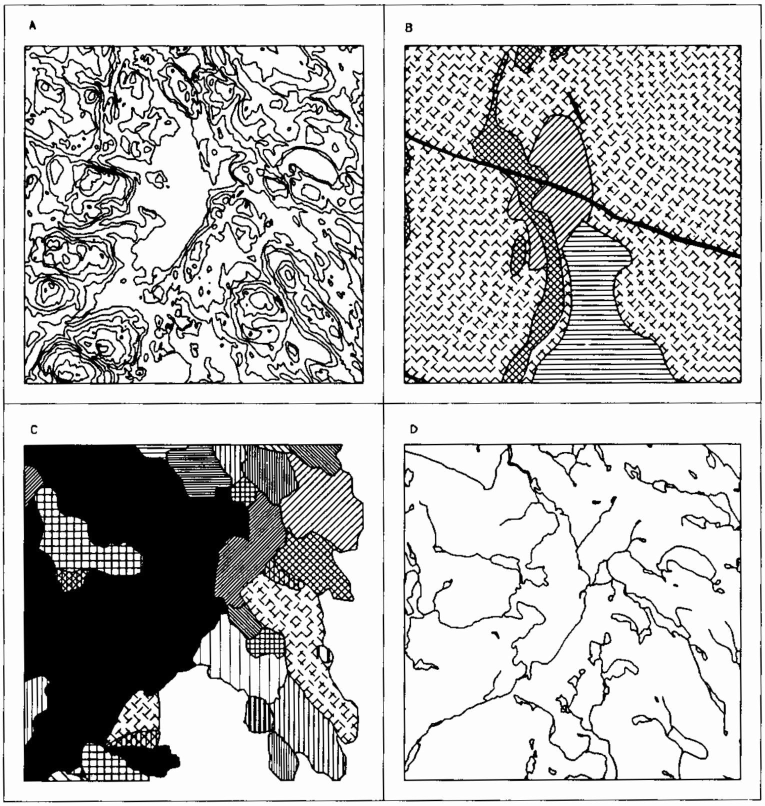
Hélie et al. (1993) correctly argued that "counts and measures data are an integral part of ongoing modelling efforts to describe and predict the effects of anthropogenically induced acidification on surface water." The integration of remote sensing and GIS tools permitted them to address three critical characteristics of the surface water bodies in eastern Canada: extent, size, and the numbers deemed to be at risk due to acidification.

Wanapitei/Algoma Dissolved Organic Carbon Study

At a much larger scale, similar integration of remote sensing/GIS tools is being performed in northeastern Ontario. The remote sensing lakes monitoring study described earlier in this chapter found a correlation between water color as measured by TM and lake DOC concentration and pH. This study is being expanded to include GIS with two goals in mind: to develop our understanding of watershed-water quality processes; and to improve the ability to interpret water color and hence water quality monitoring capabilities.

There are two study sites: the Wanapitei area north of Sudbury, which has been affected by acid rain, and the Algoma area north of Sault Ste. Marie, which is relatively pristine. GIS databases have been developed for both sites that include information from many different sources. Field surveys have provided water quality information for about 150 lakes in each area. Existing map data have been digitized, giving coarse descriptions of geology, surficial deposits, and soils. Topographic maps have been used to develop digital terrain models of the landscapes, and from these, secondary layers have been developed including

FIGURE 23.9. Selected thematic maps from the geographic information system layers of the Wanapitei area Dissolved Organic Carbon Study. (**A**) elevation contours; (**B**) geology; (**C**) watersheds; (**D**) lakes and streams.



slope, aspect, and watershed boundaries. Vegetation cover has been classified using TM imagery, which also provides water color measurements for all lakes. Some of the GIS layers that are being used in the Wanapitei study area are illustrated as separate maps in Figure 23.9.

The next step is to address the interactions between these landscape components. Most of the colored DOC in a lake comes from the surrounding watershed and wetlands. Anthropogenic acidity removes this DOC from the water, making the lakes clear. But some lakes are naturally clear, and their transparency does not mean that they are acidic. The intent is to develop GIS models describing how DOC moves from a watershed into a lake. By combining such models with TM measures of color, it should be possible to monitor pH and DOC even more accurately.

The Wanapitei/Algoma study represents a significant step of combining remote sensing and GIS through the development of an integrated view of the landscape. This is an important move in the progress of these complementary technologies for monitoring environmental health.

Future Developments and Applications

The examples of remote sensing and GIS for mapping and monitoring environmental health that have been outlined in this chapter represent a minute fraction of the capabilities of these technologies. We have only dealt with one sensor program, Landsat. But in this and many other space and airborne scanning programs, rapid progress is being made to enhance our ability to characterize and discriminate earth features, particularly by increasing the spatial, spectral, temporal, and radiometric resolution of the scanners. At the same time, image processing and GIS software is becoming more sophisticated with a trend toward more automated methods of environmental assessment.

These trends are welcomed but must be accompanied by true landscape integration (Dobson 1993). Remote sensing brings a constantly updated view of the status of earth and environmental processes. GIS has powerful spatial analysis tools with which to interpret the vast store of geographic information in databases and imagery. But the challenge of the future is to combine both technologies with quantitative models describing the processes and interconnectivity of the many elements of the landscape. Then and only then will remote sensing and GIS be fully appreciated by the scientific community and reach their true potential in local and global natural resource management and monitoring.

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