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Statistical Aspects of the Application of Geographic Information Systems in Canadian Environment Statistics

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Abstract: Geographic Information Systems (GIS) permit the environmental statistician to combine highly varied data within geographic units that are natural for environment analysis. A GIS forms the core of the Statistics Canada Environmental Information System, which organizes spatial data, non-spatial data and a reference system to environmental data bases. GIS provides the ability to input, edit, transform, analyze, manage and output spatial data. The use of GIS raises several statistical issues: how to document data quality, means of assessing georeferencing error and errors arising from topological properties of the spatial units being analyzed, and concerns over statistical validity and the preservation of confidentiality when working with small geographic units. While complex to manage, GIS offers modes of analysis which were formerly impossible or prohibitively expensive; their use has permitted the rapid development of the Canadian Environmental Information System.

Key words: Geographic Information System; GIS; environment statistics.

1. Introduction

While many environmental problems are global in scale, such as the release and accumulation of greenhouse gases and substances that destroy ozone, a significant proportion are local or regional in character. For these problems the source of the disturbance and the environmental response are closely associated in space and time. This implies that for national jurisdictions, knowing the geographic location of discharge points and measurement points for concentrations of contaminants in environmental media is as important as knowing the quantities. For the environmental statistician, therefore, Geographic Information Systems (GIS) as tools specifically designed for dealing with spatial data hold considerable promise.

A concise definition of GIS was given by Jackson, James, and Stevens (1988, p. 78): "a computer system for the efficient input, storage, manipulation, analysis, representation, and retrieval of all forms of spatially indexed and related descriptive data." They also point out that the development of GIS is not new – Crain and Macdonald (1984) documented experience with the Canadian Geographic Information System spanning some 20 years.

The essential feature of GIS for the

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environmental statistician is the capacity to combine disparate georeferenced data (i.e., data with an explicit geographic locator, such as longitude and latitude, as an attribute) within common geographic units. This capacity is being widely exploited in environmental analysis and natural resource management in North America.

Olson, Durfee, and Wilson (1986) documented the use of the Oak Ridge National Laboratory GIS in models of the effects of acid deposition in the Adirondack Mountains; the models depended on data concerning bedrock, soils, land cover and land use, deposition and water chemistry. Risser and Iverson (1989) describe the GIS being used for natural resource management by the State of Illinois: data sets included in the system span biology, geology, hydrology, administrative units and infrastructure and special features. Ehler, Basta, LaPointe, and Warren (1986) are using GIS in the construction of oceanic and coastal atlases for the United States covering physical and chemical characteristics, biological characteristics, economic activities and environmental quality.

This article will first describe the use of GIS in the Canadian Environmental Information System, then discuss some of the statistical issues raised by the system.

2. The Canadian Environmental Information System

The Environmental Information System (EIS) currently being developed at Statistics Canada is intended to serve two purposes: (i) to provide environmental data to the public, and (ii) to support the production of State of Environment —(SOE) reports as a vehicle to inform the public. Statistics Canada is a partner with Environment Canada in a program of national SOE reporting.

Determining what to measure in a statistical system requires a conceptual framework. The "environment-economy model" underlying the EIS encompasses the following elements:

- Socio-economic activities provide goods and services to the population. They depend on flows of materials and services from the environment (e.g., extraction, cropping, and recreation), and produce effects on the environment through flows of by-products and restructuring.
- Environmental systems respond through changes in air, water, and soil characteristics and changes in biotic state (species mix, diversity, size, and regenerative capability).
- Changes in environmental systems affect the socio-economic system through degradation of agricultural land; transport of air pollutants which affect humans, artifacts, and living resources; accumulation of pollutants and excess nutrients in water (affecting potable water supplies and fisheries); depletion of living stocks; and global effects such as increased incident ultraviolet radiation, greenhouse warming, and unstable weather.
- The socio-economic system responds to environmental change through policy and legislation (e.g., mandated pollution abatement, reclamation of damaged landscapes, and changes in cropping practices in agriculture and forestry).

This framework suggests the types of data that we wish to measure and store in the Environmental Information System:

- economic activity levels
- flows of by-products into the environment
- restructuring of natural systems
- changes in physical and biotic state

- changes in resources on which the socio-economy depends
- public and private investment in pollution abatement and control and environmental rehabilitation
- environmental legislation

This organizing framework for the Environmental Information System is related to the STress-REsponse Statistical System (STRESS)(Friend and Rapport (1979)).

With this as a conceptual background, the Canadian EIS consists of three major components:

The Tabular Management System contains summary data and information that has no specific geographic identifier. Expenditures on environmental treatment, descriptions of legislation, and national-level summaries would be examples of data residing in this portion of the system. Data to support international reporting requirements would be kept up-to-date in this part of the system.

The Reference Management System is a meta-data base, i.e., a data base about data bases. There is no intention to store all source data in the EIS (e.g., there would be little point in storing raw monitoring data)- a reference system that points at data sets not in the system is therefore required. This will contain information about data set names, variables measured, periodicity, extent, location, and contact point.

The Geographical Information System contains all data for which the geographic location is known. This is described more fully below.

2.1. Previous experience compiling environmental data

The starting point for most statistical endeavours is the definition of classifications. Subject matter experts have classified the various physical and chemical substances that are measured in data on emissions and ambient concentrations in environmental media, as well as the characteristics of the Canadian landscape – land use, land cover, soils, geology, biota, and so on. Work on environmentally useful classifications of human activities has been carried out at Statistics Canada, such as the definition of high-, medium- and low-stressor industries (i.e., industries categorized according to the extent of their effects on the environment). One key element of work on environmental reporting has been the definition of geographies that are relevant for environmental analysis.

The issue of geographic units for reporting and analysis is clearly important for a country of some 10 million square kilometers. Most data are collected within political or administrative boundaries, for example, census enumeration areas, municipalities, and regional resource management areas. Obviously, environmental problems and environmental effects do not respect administrative boundaries. Work over the last several years at Statistics Canada and Environment Canada has concentrated on the development of standard reporting and analysis of geographies. The basic set of geographic boundaries for environmental reporting is as follows:

- A 127 km grid for air pollution measurement and display.
- Drainage basins, broken down into sub-basins and sub-sub-basins.
- Ecozones (15 broad zones are defined for Canada), broken down into 300 ecoregions and 5400 ecodistricts. This ecological land classification was based on the prevalence of landforms, water, soil, vegetation, climate, wildlife, and human interventions. These are described in Wiken (1984).

Having defined boundaries for reporting environmental data, the main problem is that of aggregating to these boundaries. Our experience in publishing environmental compendia suggests that the ability to map these data within environmentally relevant geographies is extremely valuable.

In the past the process of compiling environmental data and publishing them in cartographic as well as tabular form has been expensive. Many maps had to be hand compiled from printed originals. Data, even where available in machine-readable form, were wildly disparate in format, level of aggregation, and geocoding. Special-purpose software had to be used to aggregate geocoded data to new boundaries for environmental reporting. This was the process used in publishing two editions of *Human Activity and the Environment* (Statistics Canada (1978, 1986)). The second edition employed many of the above geographic classifications to organize a variety of socio-economic and environmental data. Perhaps the most serious problem with this process is that data, when published in a statistical compendium, are static: if the data as presented fit the user's needs exactly, then all is well. However, if a user wishes to see variables aggregated in a different manner or summarized for a different reporting geography then the only option is to return to the source data and repeat much of the work that went into producing the compendium in the first place. There is also the problem of timeliness – many data are out of date by the time they are published.

3. Geographic Information System Capabilities

Geographic Information Systems (GIS) are designed to overcome the shortcomings of traditional methods of data management in dealing with geographic detail. They are distinguished from traditional data base systems in that topological information is combined with thematic data – the result is a marriage of cartography and data base management.

In current GIS technology there are two dominant data models for representing geography, vector-based and raster-based systems. The GIS in use at Statistics Canada combines a vector data model with a relational data structure, and the description which follows relates to these characteristics; the system was described more fully in Dangermond (1983).

The basic topological features recognized by the GIS are points, arcs, and polygons. Thematic data can be associated with any of these features, so that pollution emmission readings may be tied to a particular point, and measurements of ambient concentrations to a polygon representing a river subbasin. Both topological data and thematic data are stored within a uniform data structure, called a *relation*, permitting a great deal of generality in the types of operations that can be performed.

A relation may be conceived as a table in which the rows are called "records" and columns "attributes" – a record for an individual measurement at an air monitoring station, for instance, would have attributes corresponding to the associated topological feature (e.g., a point representing a specific geographic location), the date, and the various physical parameters measured (particulates, sulfur oxides, etc.). The data base management system that implements these relations permits a high degree of abstraction, in that the user can refer to attributes by their name without knowing anything about how they are physically stored. Different relations may be combined (technically this is called a "join") to display related information, e.g., to show both air and water monitoring measurements at a given location. Powerful capabilities exist to select records based on complex logical relationships between attributes – for example, to display all polygons where sulfur oxides in air exceed a certain concentration for more than 30 days in the year.

The combination of a relational data base management system with a scheme for representing topological information within the same data structure is the "engine" of the GIS. To make it a practical working tool for the environmental information system several other functions are provided:

- *Input and editing.* The system can capture input data in a variety of ways. Cartographic information can be digitized or read in digital form from another system, then editing functions applied to dissolve small polygons into larger ones and eliminate overshoot and undershoot in the sets of arcs making up polygons. Thematic data can be converted from several external formats.
- *Transformation.* Cartographic information must be converted between a variety of means of specifying location and representing projections.
- *Analysis.* Capable analytical tools are available. Thematic data measured at points can be aggregated to polygon boundaries. Creation of "buffers" as automatically generated polygons around point or arc features is possible. Overlays of thematic data can be performed and cross-classifications created – e.g., the intersection of polygons where high pesticide application occurs and points representing the nesting sites of sensitive bird species creates a new classification of areas where bird species may be at risk. Statistical measures and cross-tabulations can be produced.
- *Data management.* Tools exist to create and modify the relations making up a data base and to maintain a "data dictionary" which defines the relationship between internal storage formats and attribute names in a given relation. The data dictionary documents both relations and attributes within relations. A library system for cartographic information is used to keep track of maps.
- *Output.* The system permits a wide variety of output, including digital files in standard formats that may be read by other systems, maps produced on plotters, and reports of tabular data.

A typical use of the geographic information system would be to compile and store thematic data with their associated geographic location, e.g., production by industrial sector, discharges, measures of loadings, etc. Next the analyst selects or constructs the reporting geography of interest, for example ecozones or drainage sub-basins. The thematic micro-data are aggregated to these boundaries and reporting variables defined. Finally maps and tables of these variables are produced.

The GIS approach to environmental information has several clear advantages: (i) highly disparate data, in terms of aggregation, geographic classification, and external storage format, can be handled; (ii) human activities, stresses on natural systems and environmental responses – in other words, a wide variety of types of data – can be juxtaposed in their geographic locations, (iii) there is no fixed reporting geography or level of aggregation, so these can be adapted for the presentational or analytical purpose at hand; and (iv) it is straightforward to load special-purpose data sets that may be combined with existing data in the system for analytical studies.

4. Statistical Issues in the Use of GIS

While not specific to the application of geographic information systems, there are important differences in the nature of traditional socio-economic data and much environmental data. These may be summarized as follows:

Extensive vs. Intensive Measures. Most socio-economic data are extensive (number of individuals, value of shipments, etc.) and so may be summarized to provide aggregates. A substantial portion of environmental data is intensive, relating to concentrations of pollutants in environmental media for example, and so requires additional information on volumes or flow rates in order to permit aggregation.

Measurement Error. Most socio-economic data are survey-based; measurement error relates to questionnaire design and human behaviour as well as cognitive processes; quantifying the difference between what you wish to measure and what you actually measure with a survey may be problematic. Most environmental data are measured using scientific instruments for which calibration standards can ensure repeatability.

Sampling Error. For socio-economic survey data there are well-developed theories of sampling from populations which permit the estimation of error bounds. For a considerable body of environmental data the underlying distributions are not known; sampling error may relate to time, the sampling frequency compared with the potential rates of change of the phenomena being measured; or it may relate to space, the number and distribution of sample points required to draw conclusions about larger geographic units.

Since the GIS component of the environmental information system combines these different types of data, to be consonant with the framework described in the previous section, it is worth noting their differences. The statistical issues relating to the use of GIS are summarized under three headings: quality; georeferencing and selection error; and confidentiality.

4.1. Quality

An important element of assuring the quality of data residing in the GIS is the establishment of clear criteria for data selection. For the environmental information system this implies answering the following questions:

- Can the information indicate environmental state or processes of change?
- Can it be related to other data?
- Is the information defensible (e.g., if not scientifically collected, such as data from amateur bird-watchers)?
- Can it be summarized or distilled to a few significant series?
- Does it contain geographic detail at a regional or national level and are the standards of measurement consistent across the geographic space?
- Are there time series? Is the date of measurement consistent across the geographic space?

The keystone in documenting the quality of data series in the GIS is the data dictionary. For each relation there is documentation of its provenance, descriptive text and measures or assessments of statistical reliability; for each attribute of the relation there is a description and a unit of measure. For each extraction of data from the GIS, therefore, there must be accompanying text from the data dictionary, rather like the footnotes to a table, indicating its origin and quality. Of course, when combining different data into composite measures the usual rules of reporting error bounds apply.

The capacity to work with small geographic areas inherent in GIS means that particular care must be taken in the use of survey as opposed to census data. Sample sizes must be measured, and consequences for statistical accuracy assessed, for extractions from survey data.

While not a data quality issue *per se*, the management of units of measure can often be a source of error. The GIS will typically contain data in a variety of physical and monetary units over a range of scales from billions to billionths. Particular care must be taken in ensuring common units of measure over time, especially where survey instruments may vary slightly from one period to the next.

4.2. Georeferencing and selection error

Working with georeferenced data entails one new source of potential error: the accuracy of the georeferencing itself. In addition, there is the possibility of "selection" error when overlay techniques are used to select data for further operations (e.g., aggregation) or analysis. The two most important variants of the overlay are:

- Point–polygon overlays classify a set of points according to which polygon they lie within – an example would be classifying water monitoring stations according to the sub-basin of a watershed within which they reside.
- Polygon–polygon overlays create a new set of polygons from the intersection of other sets of polygons – an example would be overlaying soil type polygons and land use polygons to show, for instance, which prime agricultural land has been converted to industrial or residential use.

Georeferencing error often arises in performing point–polygon overlays, in which there is a degree of uncertainty as to whether points near a polygon boundary are actually on one side or the other of the boundary. Most GIS systems include an elegant tool for analyzing these problems: automated buffering. It is possible to generate new polygons representing buffers of specified width around any point or arc feature in the data base – therefore "zones of uncertainty" may be drawn around points, representing the georeferencing error, whose intersection with the polygon boundary may be used to calculate error bounds in analyses using the polygons.

Making selections of data using overlay techniques can also be a source of error depending on the nature of the data. Point data are specifically tied to a reference point; polygon data are tied to an area and, to a considerable degree, uniformly distributed over that area. What may be termed "quasi-polygon" data present the most problems and come in two varieties:

i. The data are associated with a boundary but there is no guarantee of their uniformity of distribution over the area of the polygon.
ii. The data are associated with a point, typically the centroid of a polygon, but there is no digitized polygon boundary or guarantee of the uniformity of distribution of the data over the area of the polygon.

The second of these is precisely the situation faced in the construction of the Statistics Canada EIS where Census Enumeration Areas (EA – representing data on some 300 individuals), with georeferenced population centroids but no digitized boundaries, are the smallest geographic unit for which data on population and agriculture are stored. It is worth exploring the sources of error which can arise in the use of these data.

As long as one is working within the hierarchy of census geographic boundaries there is no problem of selection error. Because the boundaries from a hierarchy, aggregation of enumeration area data to the next level (census sub-division) is as accurate as the

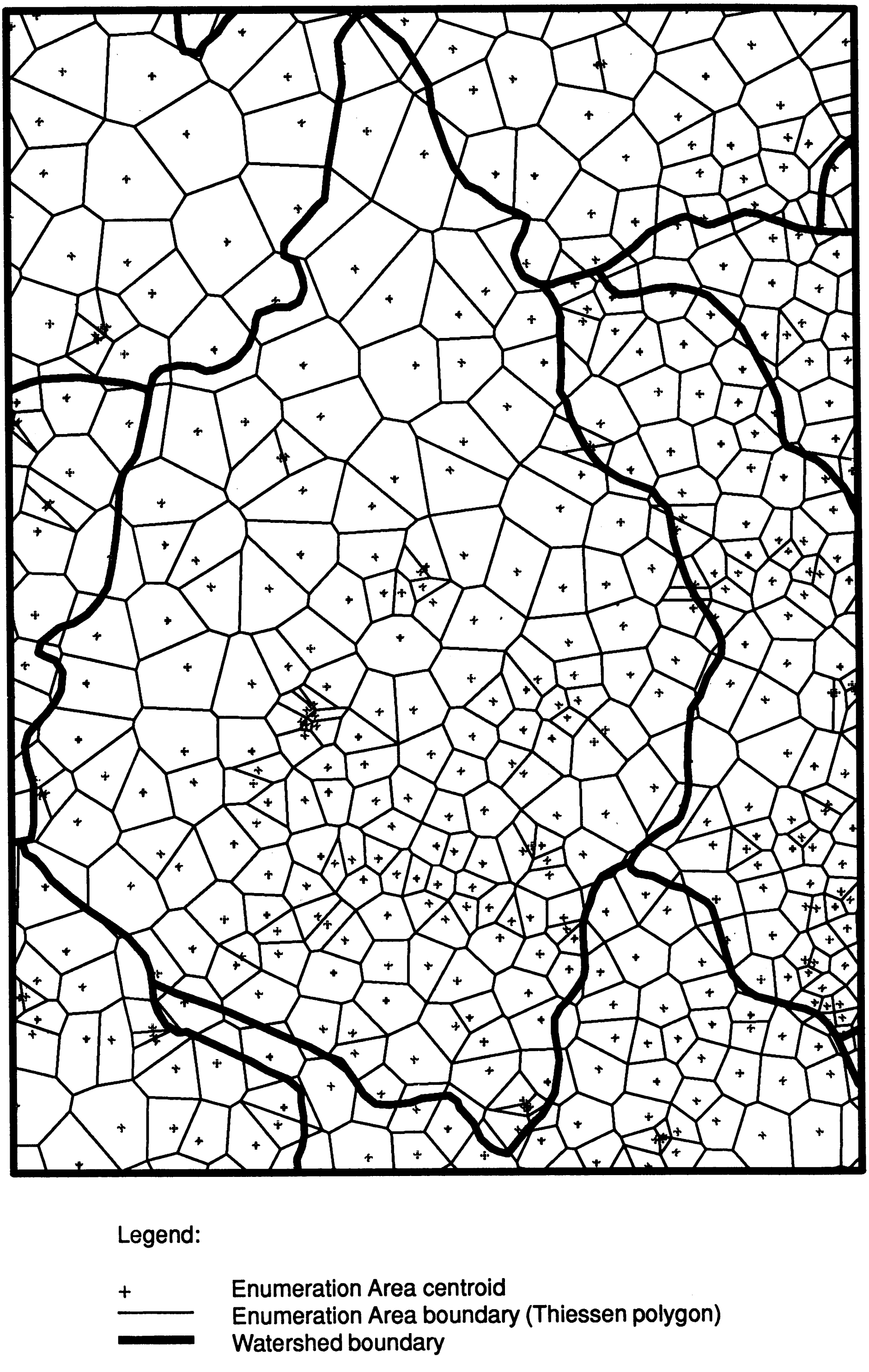

Fig. 1. Point and polygon features, Grand River Basin

census-taking process permits. The problem in the EIS is that the polygons representing natural units of analysis (ecozones and watersheds for example) do not form a hierarchy with enumeration areas – selection error arises from the "ragged" overlap of EA's with the natural boundary whereby, for EA's near the boundary, some of the EA lies within the boundary and some outside (an example of the point and polygon features for enumeration area data is provided in Figure 1). The sources of error in aggregating EA data to these natural boundaries are threefold:

i. Geometry – the larger the size of the natural unit relative to the EA, the smaller the zone of uncertainty at the boundary. As well, if the natural unit has some portion of its boundary corresponding to a natural barrier, such as a large body of water, it is likely that EA boundaries will also respect the barrier, thereby reducing selection error.

ii. Uniformity of the distribution of a variable across adjacent EA's – if there is large variation then large errors can occur at the boundary of the natural unit.

iii. Uniformity of the distribution of a variable within EA's – lack of uniformity can lead to large errors at the boundary of the natural unit, although sufficient randomness in the distribution within EA's should lead to cancellation effects.

It is instructive to compare a point–polygon match with a polygon–polygon match for EA based data – the example chosen relates to the major agricultural watersheds in southern Ontario, as shown in Table 1. The variable of interest is total farmland area by watershed in 1986. Since digital EA boundaries do not exist for 1986, the following simulation was performed to arrive at polygon–polygon estimates: (i) Thiessen polygons (see Boots (1980)) were generated for each EA centroid; (ii) farmland within the EA was assumed to be uniformly distri-

Table 1. Farmland area by watershed in southern Ontario, 1986

Watershed identifier	Number of EA's	Point–polygon area estimate (000 ha.)	Polygon–polygon area estimate (000 ha.)	Percent difference
943	125	266.7	273.3	2.4
944	38	105.5	97.0	−8.8
945	230	327.7	341.5	4.0
946	176	86.5	94.3	8.3
947	188	97.7	97.0	−0.7
948	98	224.6	220.9	−1.7
951	149	261.5	252.3	−3.6
952	120	244.2	251.2	2.8
953	237	137.2	144.5	5.0
954	142	114.0	120.1	5.0
955	224	318.8	314.0	−1.5
956	154	190.1	197.1	3.5
957	137	305.3	303.8	−0.5
958	54	73.3	77.3	5.1
959	155	137.0	129.9	−5.5

buted over each polygon; (iii) after the watershed boundaries were overlaid on the Thiessen polygons, the farmland area within these polygons was apportioned to watersheds according to the proportion of the area of each polygon which lay within the watershed.

This example has some interesting implications. The difference between the point–polygon and polygon–polygon estimates is small, less than 9% in absolute value with a mean near 5% – as expected, there is moderate correlation (−0.6) between size of watershed (as represented by total farmland area) and the absolute value of the percentage difference in the estimates of area. It is not possible to say that one method is more accurate than the other given the uncertainty about the distribution of the variable (farmland in this example) within the EA boundaries. In fact, if the variable is likely to be spatially correlated with the population centroid (as is the case for farmland) the point–polygon method may be preferable. For enumeration area based data, therefore, as long as the natural boundary used for selecting data is reasonably large, point–polygon methods of aggregation give reasonable accuracy. This is important since the point–polygon match is among the least computation-intensive GIS operations.

4.3. *Confidentiality*

As in the case of sample sizes for survey data, the ability to work with small areas inherent in the GIS will accentuate the problems of preserving confidentiality of respondents. This is not expected to be a problem for agriculture and population data, but will be for industry data.

GIS technology does not offer any magic solution to this problem. For any selection of data, standard criteria for establishing confidentiality (cell counts and concentrations) will have to be applied. Standard means of dealing with confidential cells will also be applied before release of the data: suppression or placing data in ranges.

Since these are data for environmental analysis, novel aggregations may permit pooling of cells to reduce problems of confidentiality – for instance, aggregating industry data according to whether the industries are high, medium, or low stressors of the environment may still provide useful numbers.

Finally, the capacity to work with small, *ad hoc* boundaries in the GIS increases the risk of residual disclosure. For sensitive figures such as the industry data this may mean releasing data only for standard, relatively large areas.

5. Conclusions

The capabilities provided by geographic information systems do not come without cost. Most obvious are software and hardware costs: the software is large and expensive and makes heavy demands on computing capacity, both processor and storage. However, by now GIS software is available on the full range of computers: PC's, workstations, minicomputers, and mainframes. The continuing exponential decrease in cost per unit of computing capacity means that GIS technology is increasingly affordable.

By far the largest elements of cost are related to the complexity of the system. Formal training and extensive experience in the use of the GIS are required by project staff. There is a large variety of standard interchange formats for geographic files and thematic data, but the costs in staff time of loading, transforming, and checking each individual data set are substantial. Geographic boundary files require checking for accuracy and artifacts of digitization. As in any data base project, resources must be assigned to keeping data up to date. Finally, the size and complexity of the system is itself a management challenge: standards are required for the organization of data in the system and, most importantly, the data dictionary must be kept up to date.

Balanced against these costs are the manifest benefits of GIS technology. For the statistical agency it greatly increases the value of existing data by permitting spatial analysis based on these data; the application of socio-economic data to environmental analysis is a specific case of this capacity. By making geographic location an attribute of data in the system, GIS provides the means of relating and combining data available in many domains, including remote sensing, geology, biology, and environmental monitoring as well as socio-economic surveys – this in turn will lead to modes of analysis based which were previously impossible or prohibitively expensive.

This enhanced data base capability will not eliminate the need to publish environmental statistics handbooks. But increasingly these publications will focus on broad coverage and special studies, combined with a catalogue of the information residing in the computerized system – the latter will inform researchers and members of the public about the breadth of information available and how to gain access to it. The system will permit a much greater facility in meeting *ad hoc* requests for information, and will serve as a tool for analysis as well as a more traditional data base.

The Canadian EIS currently contains the main geographic boundary files and socio-economic data: boundaries include census boundaries down to the census subdivision, population and agricultural ecumenes, ecozones and ecoregions, watersheds down to sub-sub-basins, and the 127 km grid; data include the Census of Manufactures, Census of Population and Census of Agriculture – only the data of interest for environmental analysis are loaded, but links exist to the full base for these data. Next to be loaded will be the principal emissions and monitoring data. Two uses of the system are currently being published; a study of the potential effect of acid precipitation on wildlife-related expenditures by Canadians (Environment Canada (to appear)), and estimation procedures for water-related soil erosion (Trant (1989)).

The combination of cartographic and thematic data in a single data base will greatly enhance the usefulness of environmental data in Canada. But it will not improve the quality of the data by itself – the computer maxim which speaks of "garbage in – garbage out" still applies. It is likely that greater access to environmental data will lead to calls for improvement and augmentation of the data that exist. Problems of coverage, sample design, standards for measurement, and data gaps all require attention. More fundamental still are the gaps in our understanding of environmental processes and the effects of human activities on them.

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