LAND MANAGEMENT APPLICATIONS OF GIS IN THE STATE OF MINNESOTA

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Minnesota is a large state with over 20 years of experience in the application of GIS to environmental management. It has been necessary to grapple with the conflict between breadth and depth in the inventory and analysis of cultural and natural resources. Decisions are needed on issues ranging from state-wide land suitability to clean-up of pollution at an individual site. A GIS has been employed, together with a reconnaissance level database, to address a wide range of such topical issues. The chapter describes a conceptual hierarchy of planning decisions and the appropriate scale and resolution of data required to support these decisions. Case studies in five topical areas are described which exemplify the concept of 'telescoping' to the appropriate levels of decision and geography.

INTRODUCTION

Minnesota is a state with 22 million hectares of diverse landscape, ranging from rich agricultural plains, urban corridors and productive timber and mineral lands to wilderness conservation areas. This complex landscape is a large and difficult setting in which to accommodate new land uses while protecting valuable natural resources.

Over the past 20 years, the Minnesota GIS has provided application services to many government agencies. In so doing, it has been necessary to grapple with the conflict between breadth and depth in the inventory and analysis of cultural and natural resources. The challenge has been both to obtain data with sufficient detail to serve decision making and to provide uniform state-wide coverage. The various GIS applications have had differing needs, ranging from description of a state-wide picture to location of specific sites. Some experts advocate a 'bottom-up' approach, that is compiling data at the most detailed level required and then summarizing them to less detailed scales. This approach has not been possible within a reasonable budget or time-frame in Minnesota. The need for state-wide decisions has prompted Minnesota to apply a 'top-down' approach, one of developing reconnaissance level data first and later establishing a programme to compile more detailed data for selected areas. The principal objective is to apply as much knowledge, data and technology as is necessary to influence a decision. It is essential to use the tool effectively – to deal with the correct planning level, to match the right level of geography, to apply the most appropriate analytical model and to display the map results at the best scale. What follows, then, is a discussion of this dilemma in terms of decision making, data resolution and technology.

Minnesota is not the only government to have exploited GIS successfully but it is one of those with the longest experience. It will be obvious that some overlap exists between the role envisaged for GIS by Siderelis (1991 in this volume) and that espoused here; the case studies used in both chapters are, however, highly complementary and – in totality – serve to demonstrate the range and importance of

GIS in dealings with land by governments such as the states in North America.

DECISION MAKING

GIS can serve as a decision support tool at all levels of planning. Different ways exist of classifying the planning levels (see Calkins 1991 in this volume; Densham 1991 in this volume). In Minnesota, planning decisions are made at the following four levels:

- *Strategic planning* – 'whether to do it': identification and trend analysis.
- *Tactical planning* – 'what to do': assessing alternatives and targeting the issue.
- *Operational planning* – 'how to do it': managing facilities or resources to meet an objective function.
- *Project planning* – 'doing it': design and physical placement of facilities or resources.

Data resolution

Each of these decision levels requires appropriately scaled data in order to make informed judgements. For instance, project-scale data (such as road type) are irrelevant for strategic decisions, but a summary of project data (such as traffic congestion) displayed as a trend or overall pattern would be informative. The data levels that correspond to these decision levels are:

- *Strategic data* – summary statistical data aggregated to data collection units such as political or physical subdivisions (e.g. housing density) which could be mapped at a small scale on a single page, generally at scales ranging from 1 : 4 million to 1 : 500 000.
- *Tactical data* – reconnaissance inventory data compiled by general classification units (e.g. Level 1 land cover as defined by the USGS in Anderson *et al.* 1976), which can be mapped at scales ranging from 1 : 500 000 to 1 : 50 000.
- *Operational data* – management inventory data compiled by higher classification units (e.g. Level 2 land cover), which can be mapped at scales ranging from 1 : 50 000 to 1 : 10 000.
- *Project data* – engineering design data compiled by physical description units (e.g. residential structure type), which can be mapped at scales ranging from 1 : 10 000 to 1 : 500.

Although this progression is generalized, it illustrates – with possible exceptions – the value of conceptualizing GIS as a hierarchy of decisions and data.

Technology

In the recent past, the hardware and software for individual GIS applications have evolved to a sophisticated level. Although this evolution will continue, the focus of attention has shifted towards developing comprehensive databases. Lack of sufficient data currently inhibits the optimum use of GIS for most users. This limitation will also pass as data capture technology improves and more effort is spent on data entry (see Jackson and Woodsford 1991 in this volume).

The next barrier, acquiring the knowledge necessary to simulate environmental conditions, is not as easily overcome. While much of the application of GIS is currently to produce simple thematic maps or to answer simple data queries, expectations that complex models will be able to describe and predict environmental impacts of development options are rising. These expectations can be met through professionals from the academic, scientific, and political communities addressing environmental issues collectively.

CASE STUDIES

The following case studies demonstrate the range of scope (or breadth) and depth described earlier. They also involve the concept of 'telescoping' between general, small-scale investigations and detailed, large-scale studies using the same or similar data. The projects deal with acid rain sensitivity, critical erosion targeting, water resource assessment, forest resource management and mineral exploration.

Acid rain sensitivity

The Minnesota Pollution Control Agency, together with the Land Management Information Center (Anderson and Thornton 1985) and acting in response to a 1980 state statute, has developed an assessment of the potential geographical sensitivity of Minnesota's aquatic and terrestrial resources to acid rain. There are over 15 000 lakes in Minnesota so that comprehensive monitoring is not feasible. In order to understand state-wide conditions, it was necessary to measure the status of selected lakes and drainage basins and then extrapolate equivalent values for the rest. This project was done in two phases over the period 1982–87.

In 1982, the study started with the measurement of chemical characteristics, such as lake alkalinity, for 1300 lakes plus the compilation of GIS data for four drainage basins, each over 200 000 hectares in area. Through statistical correlation of lake water quality and drainage basin resource profiles derived from 1 : 250 000 scale mapping, it was possible to identify lake basins that were vulnerable to acidification. The profiles involved data on soils, geology, land use, vegetation, drainage basin size and the ratio of land to water area. Other models were developed for sensitivity of peat lands and terrestrial resources. Results from localized investigations were extrapolated state-wide to identify other potentially sensitive areas. Hence this is an example of detailed operational data at sample sites contributing to a state-wide tactical plan.

Additional field work was done on this project in 1985 and 1987 which added water quality data measures to an increased number of sampled lakes. This improved the accuracy of the sensitivity predictions. Refinements were also made to the models as additional predictive indicators were isolated. As a consequence, more precise and reliable maps were produced identifying aquatic, terrestrial and peat sensitivity to acid rain (Plate 54.1).

Critical erosion targeting

A 1982 Minnesota statute required the Soil and Water Conservation Board to target state cost-share funding on high priority areas of erosion and sedimentation. This targeting approach is designed to direct funds to areas of critical concern. Land owners in these critical areas were then encouraged to apply corrective land practice measures. A tactical GIS approach was used to identify critical small areas rather than using a more general statistical approach which could only define critically important counties (Muessig, Robinette and Rowekamp 1983).

An inter-governmental task force developed a definition of critical areas as 'areas with erosion from wind and/or water occurring on Class I–IV (high to moderately productive) cropland in excess of 2 times the tolerable soil loss (*T*) per hectare per year; or any land within 100 m of a stream or 330 m of a lake losing in excess of 8.2 metric tonnes per hectare per year'. The state-wide GIS database was used to model erosion using the Universal Soil Loss Equation (USLE) and the Wind Erosion Equation (WEE). The result of this analysis is a state-wide map (Plate 54.2) showing critical areas, together with statistics by county. These statistics were used to allocate the state's annual $1.3 million cost-share funds. County maps were used by soil conservation officers to contact land operators about preparing land management plans. About 12 200 out of 22 million hectares in Minnesota were identified as critical.

This tactical approach was adequate for state-wide fund allocation and critical area targeting but was too coarse for implementation of local erosion ordinances and farm planning. For these applications, it was necessary to shift to an operational planning level with data compiled on 1 : 15 840-scale mapping. This has been done for selected areas of the state, including Olmsted County in southeastern Minnesota. Olmsted County's planning office (Wheeler 1988) has successfully implemented an erosion zoning ordinance. Prior to a county GIS, the county commissioners were reluctant to adopt an erosion amendment to their zoning ordinance because it was unclear how non-complying sites could be identified consistently and how much of the county was affected. The process used allowed sites as small as 400 square metres to be evaluated for water and wind erosion loss. The resulting maps (Plate 54.3) and statistics gave the elected officials the evidence they needed to adopt and implement the erosion ordinance. In addition, the planners have digitized the ownership parcel boundaries in the county and matched land owners to parcels through the tax assessors' records. This allows the planners to identify the fraction of farmsteads which does not comply and allows notification of landowners (Plate 54.4). The zoning ordinance contains a series of progressive penalties for such a failure to comply.

This use of GIS allows planners and elected officials to target their funds, effort and controls in the areas that have the highest priority. In Olmsted County, for instance, 6 per cent of the land area accounts for 40 per cent of the total erosion. Correcting these problems will not affect a large number of farmers but will substantially reduce the loss of productivity and the pollution of surface water.

Water resource assessment

Minnesota is a water-rich state with its 15 000 lakes, pothole wetlands, headwaters, stream network and abundant groundwater aquifers. Because of this, there is considerable research, policy planning and GIS activity in this topical area.

Surface water assessment

As headwaters to the Mississippi River, the Red River and the Great Lakes chain, Minnesota has 11 river basins, 83 major drainage basins, and 5700 minor drainage basins. For the Relative Nonpoint Source Pollution Potential study (Fandrei 1989), an assessment was done for each of the seven eco-regions, as defined by the US Environmental Protection Agency (EPA). Potential problem areas were defined by correlating water quality records with geographical characteristics of minor drainage basins (Maeder and Tessar 1988). Profiles were developed for each drainage basin based on GIS inventories of the extent of forest lands, cultivated land, urban areas, stream shore, lake shore, silt soil, sand soil, areas of 3–6 per cent slope, those where the slope was greater than 6 per cent and on other parameters. Through regression analysis, it was determined that the extent of forests and sand soils showed a negative correlation to water quality and all others were positive. The non-point pollution potential for each minor drainage basin was then scored by summing the rank values of the water quality predictors. The extent of shore land in a drainage basin had by far the highest correlation with water quality so the weighting of its score was doubled. Special factors, such as high wind erosion, were included for some eco-regions. A series of 1 : 500 000-scale eco-region maps was produced which displayed the final scores in decile classes (Plate 54.5).

This type of study is intended to target those areas requiring the most attention and is a form of tactical planning. The map describes the geographical extent of the problem, the areas of highest priority and the overall geographical pattern. Once this is done, the next step is to address those high priority minor drainage basins at an operational planning level by applying a dynamic stormwater simulation program. The Agricultural Nonpoint Source Pollution Model (AGNPS) is such a model and was developed by the US Department of Agriculture's Agricultural Research Service in Morris, Minnesota, in cooperation with the Minnesota Pollution Control Agency. It is an enhancement of the CREAMS model. The two objectives of the model are to obtain uniform and accurate estimates of runoff quality for large drainage basins ranging from 200 to 10 000 hectares, with primary emphasis laid on sediment and nutrients, and to compare the effects of various conservation alternatives and management practices in the drainage basin.

The model simulates single storm events defined in terms of frequency and duration. For the defined storm event, the model simulates the transport of sediment, nutrients and stream flow from the headwaters to the outlet in a step-wise manner. The data must be in a raster file and can be at any grid resolution, though under 4 hectares in size is preferable. The model is data intensive and provides progressively better results as the data become more refined in resolution and classification. The results are, as already stated, in the form of runoff statistics for flow, sediment and nutrients at the outfall point or at any selected point in the drainage basin. A series of maps (such as Fig. 54.1) can be produced which describe the degree of contribution from each of the grid cells. The effects of alternative land management practices can be compared. This level of field-specific, operational planning and management is now being applied by local water planners on a case-by-case basis. Throughout the state, there is a network of surface water monitoring stations; these can be shown on a map in relation to the streams, the drainage basin

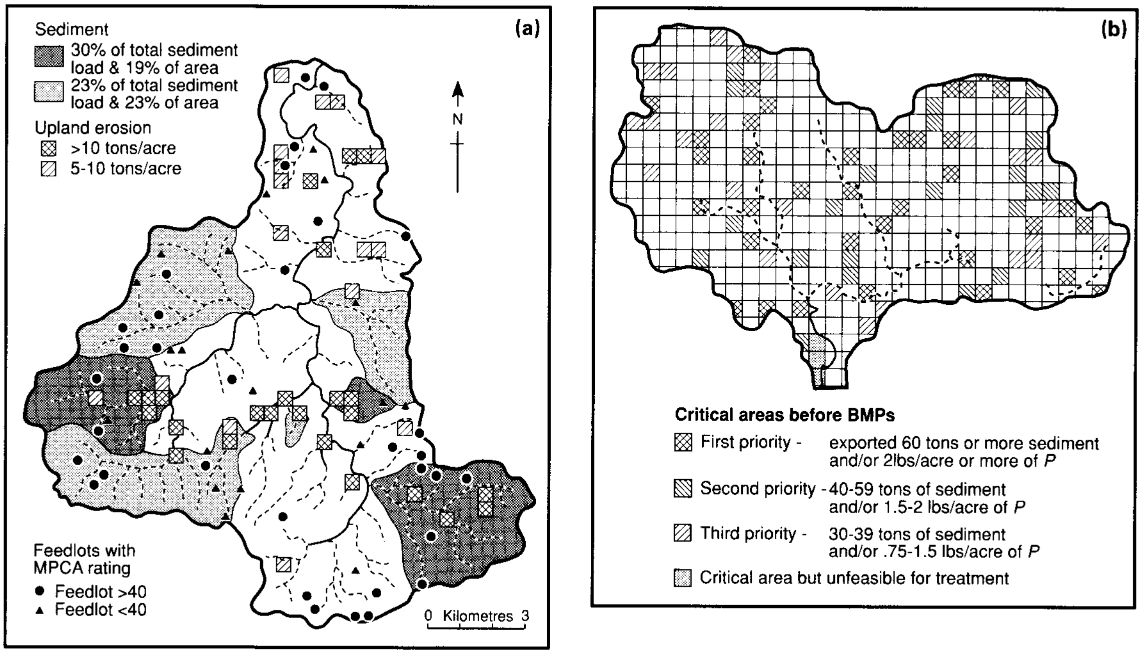

Fig. 54.1 Agricultural Nonpoint Source Pollution Model (AGNPS). (a) Estimated sediment discharge from Garvin Brook watershed, Winona County, Minnesota. (b) Estimated discharge in Salmonson Creek watershed, Big Stone County, Minnesota (courtesy USDA, ARS, North Central Soil Conservation Research Laboratory).

system and each other. The stations provide climate recording, river gauging and water quality monitoring facilities. With these stations plotted on a map, it is possible to relate them to areas of surface water problems and to correlate the monitoring records they produce with the modelling results (Plate 54.6).

Groundwater assessment

For groundwater data, there is a similar network of monitoring sites throughout the state. Observations from a network of wells are stored in a series of databases covering water levels, water quality, water appropriations, stratigraphy, etc. Plate 54.7 illustrates the distribution of water well locations by type for a county. From monitoring data, issues can be diagnosed and mapped. For instance, a review of water quality reports from public wells in 1988 by the Department of Health identified eight counties with four or more wells containing pesticides. A map of these areas can serve as an early warning that requires further site-level investigation (Plate 54.8). This is an example of displaying detailed case-level data as aggregated, summary-level data state-wide.

Another approach possible with GIS is to predict areas that are susceptible to groundwater contamination through mapping and modelling the factors involved. The selected approach is called DRASTIC and was developed by the National Water Well Association under contract to the US EPA. It is one of the few approaches designed to predict hydrogeological sensitivity to surface-derived contaminants in areas larger than 40 hectares. This system is based on major geological and hydrogeological parameters including depth to water, net recharge, aquifer media, soil media, topography, influence of the radose zone and hydraulic conductivity of the aquifer in question. Each of the above DRASTIC parameters is weighted and each individual factor (within a given parameter) is assigned a rating on a scale of 1 to 10. A map of the area to be rated is developed for each of the respective parameters using available data. A numerical score is assigned to each different factor on a given parameter map. To obtain the final

DRASTIC rating, all of the factors are multiplied by their respective parameter weights and then summed to obtain a relative score.

The study was carried out by the Minnesota Pollution Control Agency, together with the Land Management Information Center (Porcher 1989). A series of seven (DRASTIC) parameter maps was developed from available data inventories. Ratings of susceptibility were developed for each class on the maps and weights were developed for each map. Final scores ranging from 7 to 32 were divided into five susceptibility classes from lowest to highest. Well over 1000 unique combinations of the seven input parameters occur in Minnesota. This state-wide map (Plate 54.9) provides a context for concern about groundwater pollution. It represents a geographically disaggregated description of the land's ability to alternate or restrict the downward migration of contaminants to the saturated zone. It also serves as a targeting map for regulatory action and further investigation.

Sometimes the groundwater contamination problem results from a single localized source. In the case of US EPA-funded Superfund Site clean-ups, it is necessary to assess the extent of the contamination in terms of concentrations and geographical dispersion. This requires a three-dimensional approach to data display. In the vicinity of the site, historic data are sought for existing water wells and, in addition, new wells are placed to complete the monitoring needs. Water samples are tested and the results are shown in three-dimensional space in relation to surface and subsurface conditions (Plate 54.10). Readings over time can produce an animation of the contamination plume as it changes in concentration and location. These results are used in clean-up negotiation and, if necessary, in court proceedings. They provide a clear communication of facts to both scientists and lay persons. This, then, is an example of a project-level issue.

Forest resource management

Minnesota's forest resource is primarily second growth pulp wood that is used for waferboard and paper products. The state does not have a sustained yield of large saw timber like other regions. There are 5.5 million hectares of commercial timberland in Minnesota, 20 per cent of which is on state land. In order for the state to maximize the value of its forests, it must manage some of the land more intensively than it does now and with more reliance on an effective information system. A study has been carried out of state lands and their suitability to meet natural resource objectives (Minnesota Department of Natural Resources, Office of Planning 1986). In that study, a resource assessment for timber production was made using an economic timber model (Minnesota Department of Natural Resources, Division of Forestry and Office of Planning 1984). The forestry data used in this model were stand specific although the results were expressed for sections (square miles). Several factors were applied at different levels of resolution:

- forest productivity by stand;
- timber prices by area;
- management cost by region;
- distance to mill by township;
- soil expectations value by 40 acre (16 hectare) parcel.

The model resulted in assignment of sections into one of three timber management classes:

- intensive management (28 per cent);
- extensive management (33 per cent);
- custodial management (39 per cent).

Plate 54.11 shows the pattern of recommended timber management zones. This analysis demonstrates the effective use of variable resolution data. It also demonstrates that state-wide analysis can yield a result in map form with well-defined locational specification.

Another of the applications for forestry management is an assessment of land for hardwood production. Oak timber is particularly valuable for veneer products. Oak stands are scattered throughout the savanna transition zone in the state but there is potential for the management of even more. The Department of Natural Resources, Division of Forestry conducted an assessment of land suitability for oak management. This was a state-wide study using resource data compiled at a map scale of 1 : 250 000. The current pattern of oak and northern hardwoods forests is known from a reconnaissance survey by the US Forest Service. To determine what other sites are suitable for oak production, ratings were developed for soils and landform maps using their site index for oak. Those areas with high site indices should be considered (Plate 54.12). Of course, this map can be modified by overlaying higher value land uses and the extent of public lands. Even so, there are considerable opportunities for increasing the value of forest lands through improved species selection and management within 'eligible' areas identified by the GIS analysis.

Since the Minnesota forest inventory is compiled at a scale of 1 : 15 840, with stands as small as half a hectare, it is possible to use it to conduct site-level management. A mapping module is one township or 36 square miles. For each forest stand, up to 91 attributes (e.g. type, size, density) are compiled through field survey; a sample portion of an inventory map of these parameters is shown in Plate 54.13. The GIS allows a field forester to interrogate the data by asking such questions as 'Where are the mature aspen stands within one mile of road but beyond 300 feet from a stream?' This query conflates size and age, species, accessibility and regulatory setback of the woodland. The answer is provided both in map and tabular form for each area. Further assessments can be conducted to eliminate isolated parcels or areas that have higher suitability for other uses. In this way, GIS becomes a natural extension of a forester's daily tasks and serves to improve both staff productivity and the quality of decisions.

Mineral exploration

Minnesota's major mineral resource was formerly iron ore. Foreign competition and reduced ore grades have diminished mining activity in the state. In 1978, an initiative was begun by the Minnesota Geological Survey to increase the exploration activity through remote sensing for reserves. An eight-year survey measured the magnetic and gravity anomalies which are indicators of mineralization. This is done through remote sensing with flight line data on a 213-metre grid. The GIS processing includes correcting the geometry, registering the image, classifying the signals, smoothing the data and displaying them in map form. The most effective display for geologists to interpret transforms the readings into a false 3-D image, as if the readings were topographic values. A light source is then shown on the 3-D surface resulting in reflective levels with colour added to show elevation (Plate 54.14). These maps are used to target high probability mineral sites. Largely as a result of this mapping effort, exploration leases have increased from 4000 hectares in 1980 to 36 000 hectares in 1986. Many formations are being found which are similar to Canadian areas yielding gold, copper, nickel, silver, platinum and titanium. As a result of the use of this advanced information technology, it is expected that these minerals will be found and mined much sooner than otherwise would have been the case.

More detailed exploration is undertaken in areas with high mineral probability. This is usually done by assessing samples derived from drill cores, lake sediments, vegetation and rock outcrops. A GIS is an effective means of displaying and correlating the data. This has been done with the regional geochemical reconnaissance programme (Minnesota Department of Natural Resources, Division of Minerals 1989), together with the Land Management Information Center. From this sampling effort, it was possible to identify unique geochemical signatures at both the area and site levels. The resulting 10 000 hectare area was shown to have three distinctly anomalous localities based on geochemical signatures. Each of these sub-areas is shown to have many localized signatures, indicating concentrations of heavy minerals. Figure 54.2 shows the pattern of localized signatures. This type of localized operational investigation is clearly aided by the analytical and graphical capabilities of GIS.

CONCLUSIONS

These case studies demonstrate the principles described earlier. The objective of using GIS is to apply as much knowledge, data and technology as necessary to make an informed decision. It is essential to select the correct planning level, to match the appropriate level of geography, to apply the most appropriate analytical model and to display the map results at the best scale. In making these judgements, it is important to involve a

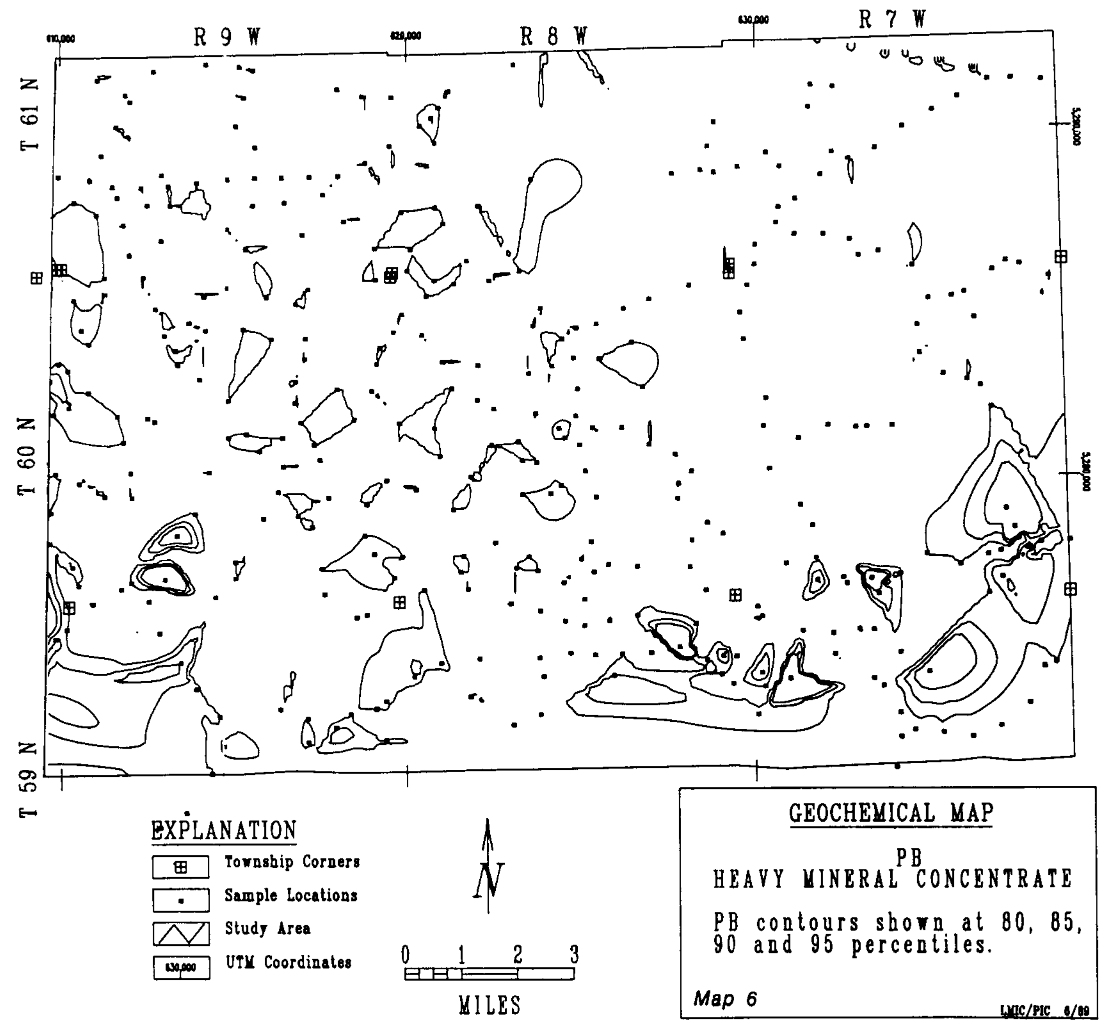

Fig. 54.2 Geochemical contour map of heavy lead heavy metal concentrate in June 1989 (courtesy Minnesota Department of Natural Resources).

variety of professionals since each will bring a bias from his or her own background. Elected officials will tend to seek more strategic and tactical answers while technicians will tend to seek a more operational direction.

In the past, the hardware/software technology of GIS was the challenge. For most systems, the database is the current challenge and the primary limitation in conducting studies. In the future, however, the limiting factor in applying GIS will be the knowledge of how to simulate environmental conditions. In pursuing these models, it is important to view them in more than scientific terms, as administrative tools to implement policies and programmes. The four levels of planning specified at the outset become a context for action, the details of which depend on what level of understanding exists for an issue and what level of geography is in question. The choice of data scale and resolution should naturally result from the needs of the scope and depth of the decision to be made. Increasingly, the technology issues will be more knowledge based than cost based as low-cost hardware/software systems become available. In the future, then, the challenge will be to apply technology appropriately to a correctly defined problem and to empower all employees to incorporate GIS technology – together with their other tools – in managing environmental problems and resources.

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