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Geographic Information Systems and Remote Sensing Techniques in Environmental Assessment

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See table of contents

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Article abstract

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Through several examples, this paper will demonstrate how remote sensing and GIS technologies can contribute to environmental assessment of an urban fringe area. Now here is the need for spatial inventories and mapping greater than in such areas, where pre-existing information becomes rapidly outdated. A 260-km2 site, north of Metropolitan Toronto was chosen as a study area. A spatial data base was constructed which included imagery from three different satellite sensors, a Digital Terrain Model (DTM), a digital drainage net work, and a digital copy of the Ontario Geological Survey's Quaternary geological map.

Geographic Information Systems and Remote Sensing Techniques in Environmental Assessment

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SUMMARY

Digital map products and spatial inventories are becoming increasingly available from geological surveys, agricultural, natural resource, environmental, energy, transportation and forestry departments. As well there are now multitudes of specialized digital airborne and satellite image products available. This wide availability of geographically referenced data and the advances in spatial data analysis software are providing geoscientists with new tools and new ways of viewing traditionally used data.

Through several examples, this paper will demonstrate how remote sensing and GIS technologies can contribute to environmental assessment of an urban fringe area. Nowhere is the need for spatial inventories and mapping greater than in such areas, where pre-existing information becomes rapidly outdated. A 260-km^2 site, north of Metropolitan Toronto was chosen as a study area. A spatial data base was constructed which included imagery from three different satellite sensors, a Digital Terrain Model (DTM), a digital drainage network, and a digital copy of the Ontario Geological Survey's Quaternary geological map.

RÉSUMÉ

Un nombre croissant de produits de la cartographie numérique et d'inventaires spatiaux sont offerts par les services de levés géologiques et les ministères responsables de l'agriculture, des ressources naturelles, de l'environnement, de l'énergie, des transports, et des forêts. Il existe également une multitude de produits numériques spécialisés provenant de l'imagerie satellite ou aéroportée. Cette grande disponibilité de données à références géographiques et les nouveautés en matière de logiciel d'analyse des données spatiales offrent aux géoscientifiques de nouveaux outils et de nouvelles façons de considérer les données habituelles.

À l'aide de plusieurs exemples, on démontre dans le présent article comment la télédétection et les technologies de SIG peuvent être utilisées dans l'évaluation environnementale des zones péri-urbaines. Il n'existe pas d'endroit où le besoin de données d'inventaires spatiaux et de cartographie soit plus pressant que dans ces banlieues, où l'information existante est si vite périmée. Une zone d'étude de 260 km^2 située au nord de la zone métropolitaine de Toronto a été choisie. Une banque de données spatiales a été créé, et elle renferme des images provenant de trois détecteurs satellisés, un modèle numérique de terrain (MNT), un réseau de drainage numérisé, et une copie numérique de la carte géologique des dépôts de Quaternaire de la Commission Géologique de l'Ontario.

INTRODUCTION

Urban planning is critically dependent upon map data and analysis of spatial information. Currently, an evolution is happening in spatial data analysis and manipulation that is having a great impact on environmental geology. Many spatial analysis functions,once treated separately and analyzed by separate software packages, can now be found in single spatial analysis software packages. It is now common to find functions of Image Analysis Systems (IAS), vector Geographic Information Systems (GIS), raster modelling Geographic Information Systems, Computer Aided Design (CAD) systems, geophysical processing software, and 3-dimensional modelling software available in one software package. As well, all the information contained in and generated by this software can be linked *via* a central Relational Data Base Management System (RDBMS) providing further analytical capabilities. Introductions to these different techniques can be found in Sabins (1986), Richards (1986), Lillesand and Kiefer (1987), Aronoff (1989), and Antenucci *et al.* (1991).

STUDY AREA

The urban fringe area chosen for this study is on the southern flank of the Oak Ridges Moraine (ORM), 20 km north of Metropolitan Toronto (Fig. 1). There is increased awareness and appreciation of the environmental importance of the

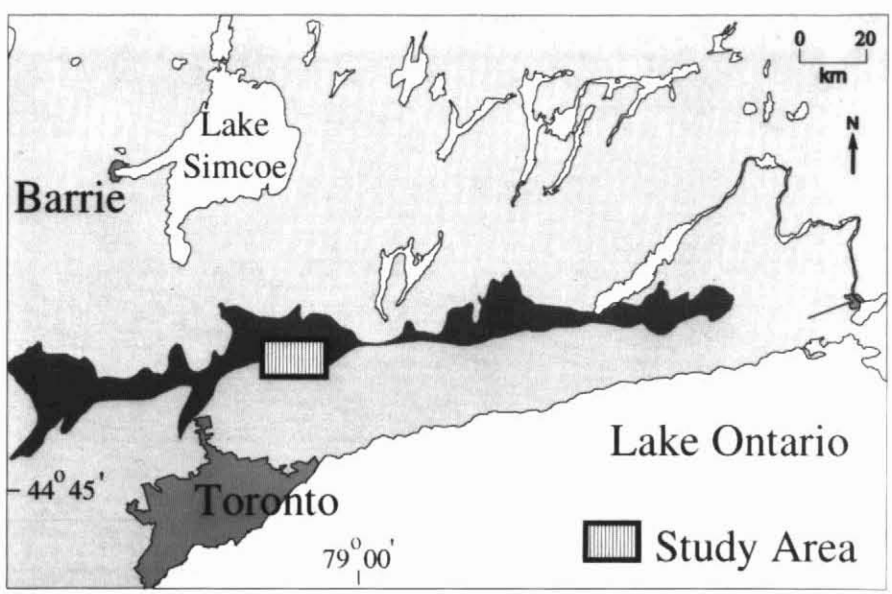

Figure 1 *The Oak Ridges Moraine and location of study area.*

moraine (Howard *et al.*, in press).

The study area is 20×13 km in size and contains the towns of Claremont, Stouffville and Goodwood (Fig. 2). Elevation varies from 140 m asl in the southeast corner, to 410 m asl at the crest of the moraine in the northeast corner. The lower relief, southern half, of the study area is dominated by the Halton Till (Eyles, in press; Howard *et al.*, in press). Also present in the south-central portion of the study area are large areas of glaciolacustrine silt and clay deposits (Fig. 3). The higher relief, northern portion, of the study area is on the ORM, and is dominated by coarse-grained glaciofluvial and ice-contact sand and gravel deposits (Fig. 3).

Land cover in the study area varies from predominately agricultural in the southern relatively flat areas, to natural and reforested tracts in the hummocky areas on the moraine. Scattered throughout the area are numerous wetlands and kettle lakes. A north/south drainage divide is present in the northern portion of the study area. The study area also contains numerous cold-water springs that feed the head waters of several streams and tributaries, including Duffins Creek, Reesor Creek, and Little Rouge Creek, all flowing to the south, and Black Creek, Pefferlaw Brook, and Uxbridge Brook, all flowing to the north (see Gerber and Howard, in press). Along many of these streams and tributaries the slopes are steep and remain in a naturally forested state. There are several large aggregate mining operations in the glaciofluvial and ice-contact deposits along the crest of the moraine.

EXAMPLES

The four examples presented in this paper were selected to provide an overview of GIS and remote-sensing capabilities to aid environmental investigations. These examples will demonstrate 1) semi-automated feature extraction from multi-spectral satellite imagery, 2) image enhancement and integration techniques for visual interpretation, 3) Digital Terrain Models for extracting terrain parameters, and 4) modelling using a raster-based Geographic Information System. The first three examples will each generate additional thematic information, and the fourth example will demonstrate how this interpreted (or derived) information can be used as input for a model to further characterize the area.

Semi-Automated Feature Extraction from Multi-Spectral Satellite Imagery

One application where optical satellite imagery is routinely and operationally used is land cover mapping. Two of the most commonly used sources of multi-spectral satellite imagery are the United States National Aeronautics and Space Administration's (NASA's) Landsat series and the French SPOT series of satellites. The imagery used for generating the land cover map for this test site was a Landsat Thematic Mapper (TM) image recorded April 27, 1985 (Fig. 4). Landsat TM is a 28-m-resolution instrument, that records imagery on seven spectral bands, three in the visible, one in the near infra-red, two in mid infra-red, and one in the thermal infra-red portion of the electromagnetic spectrum.

Of the numerous mathematical approaches of image classification or spectral pattern recognition, the method used in this study is the supervised Gaussian Maximum Likelihood (GML) method. The first step in this method is to train the classifier, *i.e.*, to gather spectral statistics for areas of known cover

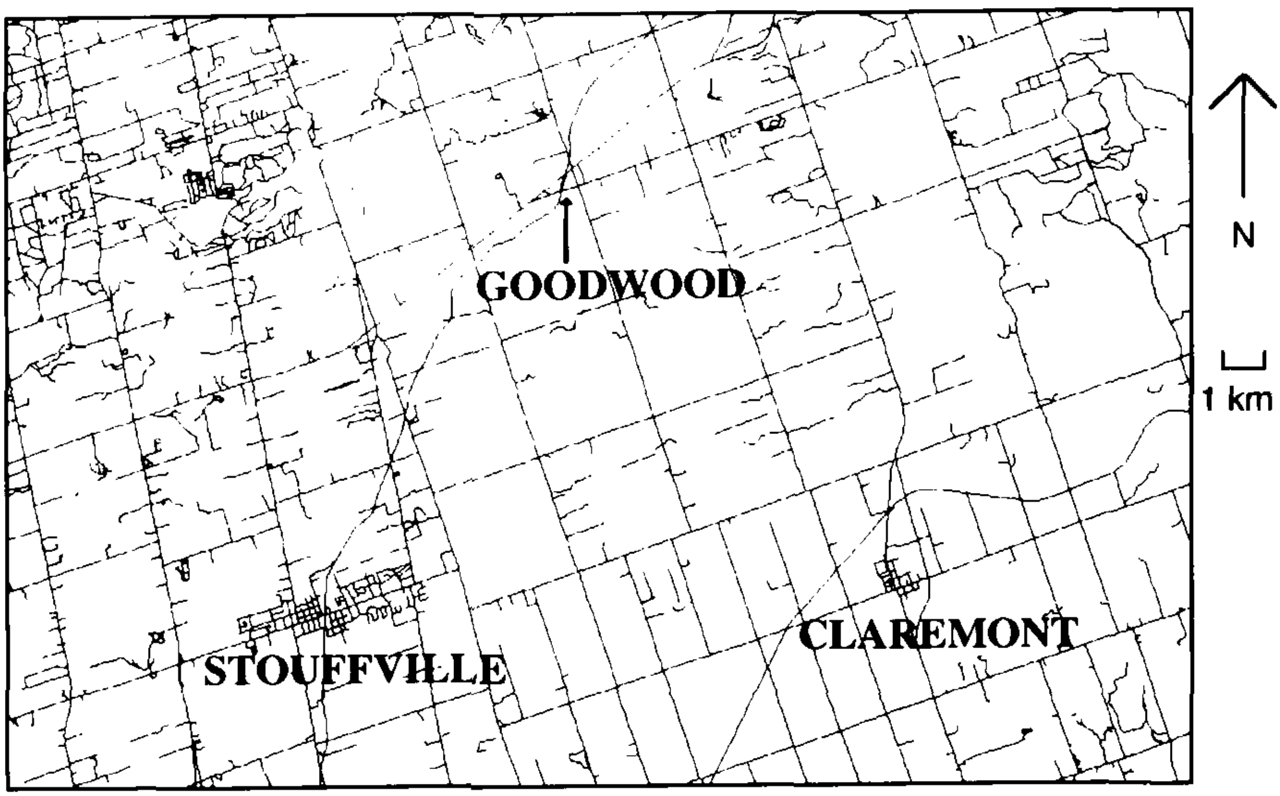

Figure 2 *Location of study area. Geographic extent; NW corner 635,000 E, 4,880,000 N, SE corner 655,000 E, 4,867,000. Note this is the geographic extent for all subsequent images and maps.*

type. This is a user-interactive task, where the user delineates areas of known composition on screen. To ensure an accurate training of the system, a user typically uses a combination of field surveys, aerial photography, and/or a knowledge of the area in this training stage. Once representative statistics are acquired for each land cover type, a complete classification for the area can be generated. The spectral signature of each pixel in the image is statistically compared to each of the known signatures and assigned to the cover type of the highest probability. For a full description of the GML technique and other multi-spectral classification techniques see Lillesand and Kiefer (1987) and Sabins (1986). A flow chart of the processing methodology used for this classification is presented in Figure 5.

From the Landsat image, 10 land cover classes were derived: 1) agricultural fields bare of crops, 2) agricultural fields with emergent crops, 3) agricultural lands, pasture or idle, 4) waterbodies, 5) wetlands, 6) deciduous forest, 7) coniferous forest, 8) mixed forest, 9) gravel pits/construction sites, and 10) urban and infrastructure (*e.g.*, roads). The result of this classification is not, however, registered to a ground co-ordinate system, and it is necessary therefore to geometrically correct this classification so that it can be used in subsequent analysis. The referencing process involves selecting identifiable points on the original image, registering these points to ground co-ordinates, and then warping, or rubber sheeting, this image or map to a ground co-ordinate system. For a full description of geometric correction methods see Lillesand and Kiefer (1987) and Sabins (1986).

Two problems were encountered with this classification that required rectification: gravel pits and quarries could not be spectrally distinguished from roads, and it was not possible to accurately classify the urban areas and portions of the transportation network. The first problem was overcome by using aerial photography as a reference and manually editing the pits and quarries to a separate class. This was not a large problem, as there were less than 20 pits/quarries in the test site. The second problem is a common land cover classification problem, and is the result of the high variability in land cover types in an urban setting. Urban areas can be composed of many cover types including roads, lawns, gardens, buildings, trees, swimming pools, *etc.* Most pixels from a 28-m instrument such as Landsat TM are the result of more than one cover type, and therefore produce mixed signatures, which can not be classified using this approach. This problem was resolved by using a digital map of the transportation network (primary and secondary roads, rail lines, *etc.*). This vector transportation map was brought to a 10-m raster representation and converted to a binary bit-map where a morphological closing operation was performed on it (Fig. 6). This process involved performing nine bitmap dilations, followed by eight bitmap erosions. This operation had the combined effect of providing a 15-m buffer around the transportation corridors while at the same time closing, or making homogeneous, those areas where the transportation network is very dense, such as suburbs and industrial areas. A 15-m buffer around most roads provided allowances for the road surface, the road shoulder, ditches and fence lines, all of which produced mis-classified pixels in the classified image. This new infrastructure/urban class was then burned, or superimposed, onto the satellite classification. Presented in Figure 7 is a generalized version of the final classification, and shown in Table 1 is a tabular summation of the land cover units in hectares. Archives of Landsat imagery

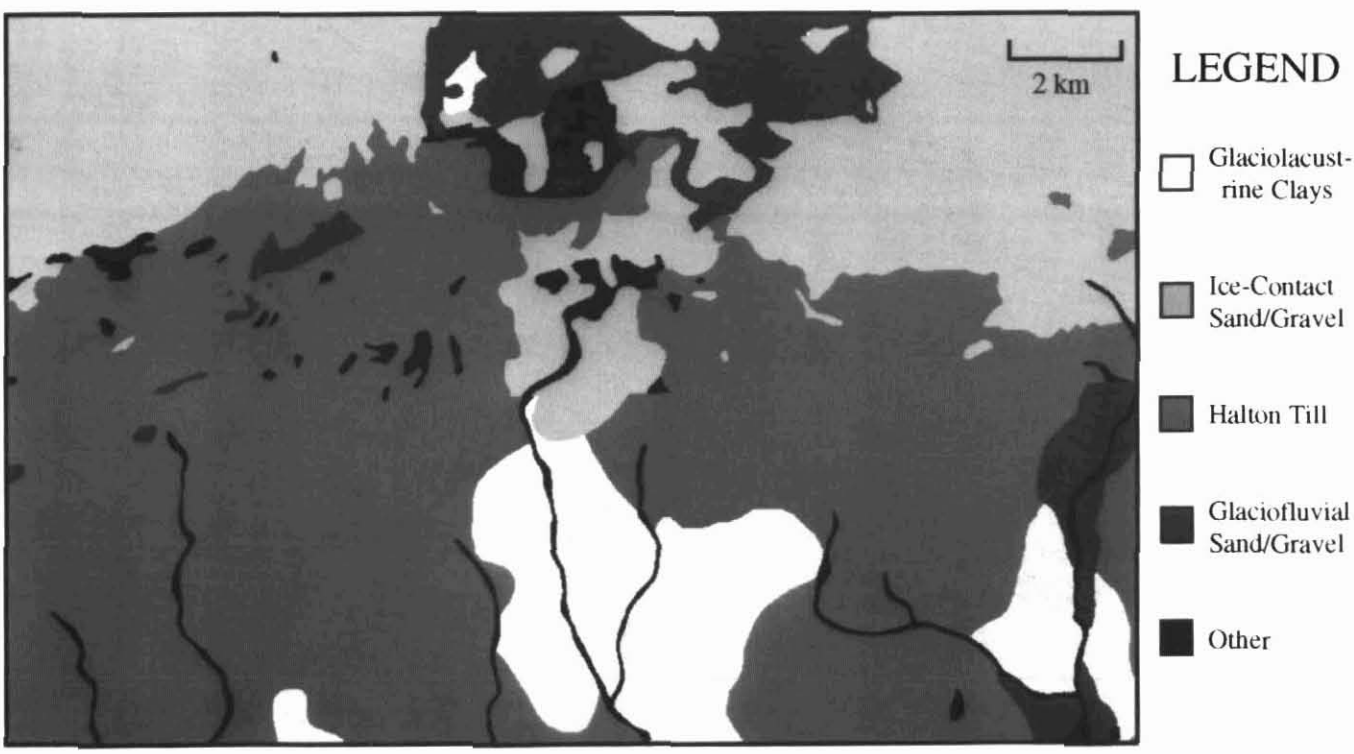

Figure 3 *Generalized Quaternary geology of the study area (after Sharpe and Finley 1993a, b; Gwyn and DiLabio, 1973 and Hewitt, 1969).*

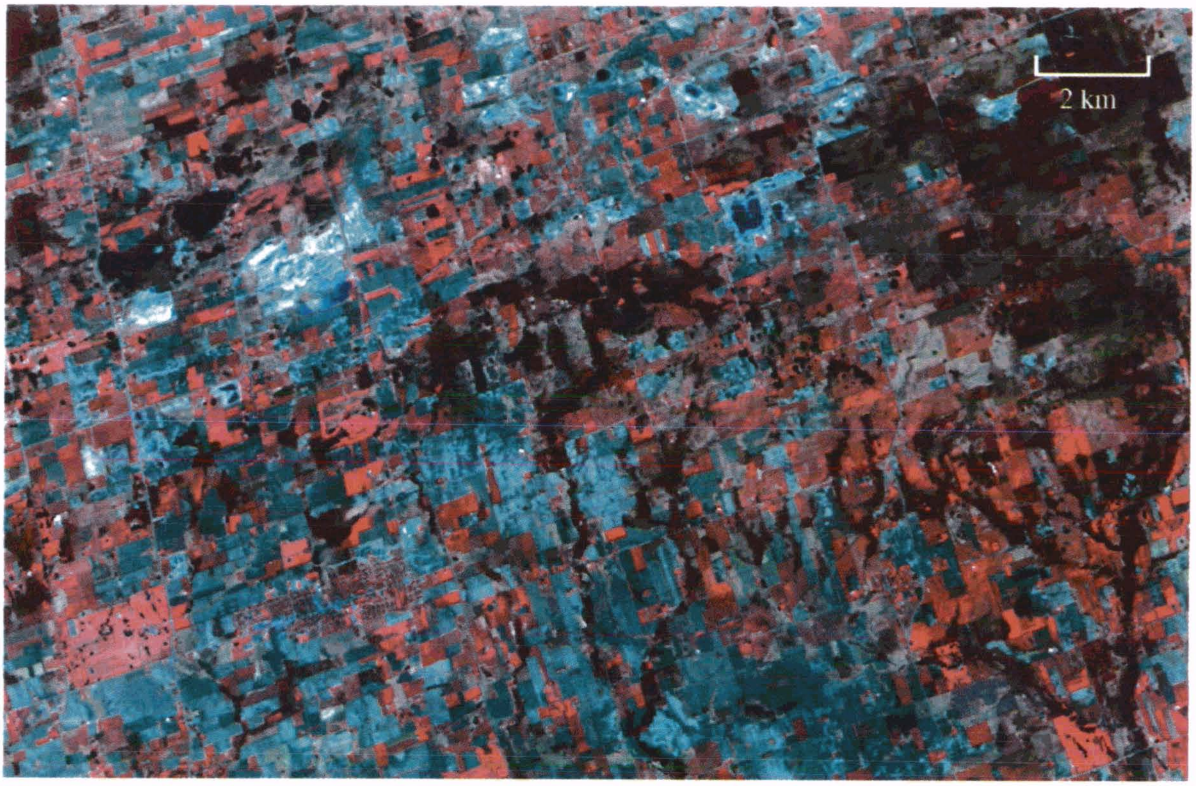

Figure 4 *Decimated, geometrically corrected Landsat TM false colour composite of the study area. Composed of band 4 (near infra-red), band 3 (red), and band 2 (green).*

Figure 7 *Land cover classification of the study area.*

go back to 1972, making it also possible to monitor and quantify land cover changes over time.

Image Enhancement and Integration for Visual Interpretation

There are many airborne and satellite sensors in operation that record digital imagery in various portions of the electromagnetic spectrum including the visible, colour infra-red, thermal infra-red, and radar frequencies. Imagery from each portion of the spectrum can contain unique geoscientific information. This data is usually in digital format, which allows it to be referenced, digitally enhanced, and integrated with other image products for visual interpretation.

Some of the most common functions include contrast stretching, spatial filtering, textural filtering, principal component analysis, band ratioing, composite generation, and colour space enhancements. As well, it is possible to generate merged images by integrating imagery from different sensors. The objective of combining imagery from different sensors is to exploit the advantages of each sensor, and create a more informative and easier to interpret image for visual interpretation. For a full discussion on image enhancement techniques for remotely sensed imagery, see Richards (1986) or Sabins (1986). For a comparison of multi-sensor image integration techniques for geological applications see Harris *et al.* (1994).

Table 1 Tabular summation of land cover units for the study area.

COVER TYPE	AREA (HECTARES)	AREA (%)
Agricultural - crops	8195	31.52
Agricultural - bare fields	6464	24.86
Urban/Infrastructure	2785	10.71
Deciduous Forest	2489	9.57
Mixed Forest	1922	7.39
Pasture/Reforested	1836	7.06
Wetlands	919	3.53
Gravel Pits/Construction	599	2.40
Water Bodies	150	0.57

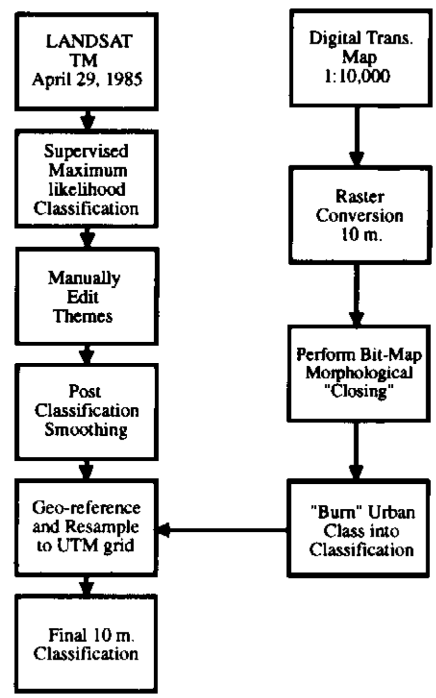

Figure 5 *Flow chart of classification methodology employed.*

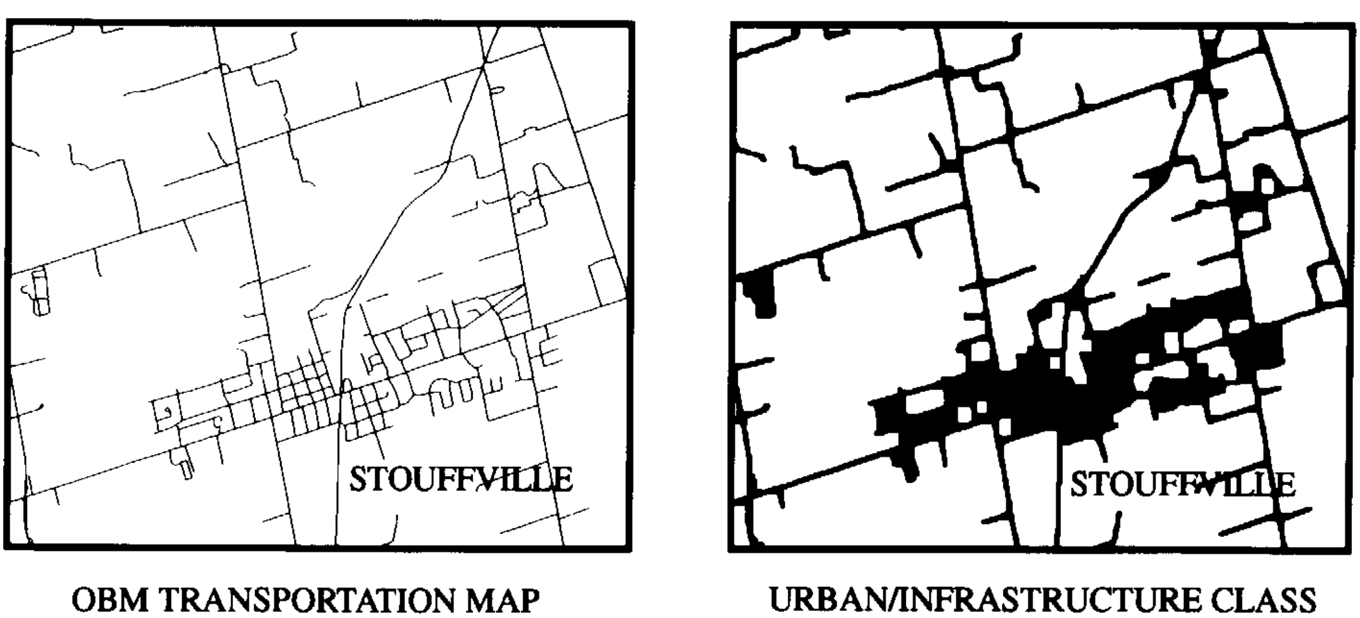

Figure 6 *A portion of the OBM vector transportation map and derived raster Urban/Infrastructure class.*

In this example, imagery from two different satellites sensors (SPOT and ERS-1) and the elevation information obtained from digital topographic maps were enhanced and digitally merged for the purpose of extracting Quaternary geology information. Each data set was referenced, filtered, visually enhanced, and then merged to a single image to provide a product that was more informative and easier to interpret than the individual data sets. A flow chart of the image-processing and integration methodology employed in this example is shown in Figure 8. A full description of the image-processing methodology employed for this study is beyond the scope of this paper, but can be found in Kenny *et al.* (1994). A brief description of the processing methodology employed and results obtained is given here.

The ERS-1 scene selected was an early spring 1992 image. The ERS-1 is a 30-m instrument operating in the radar portion of the electromagnetic spectrum. Radar images are very complex and can be resultant from many ground variables including land cover, ground cover, topographic relief, surface roughness, surficial material texture, and soil moisture content. Each of these parameters can have a direct or indirect relationship with the surficial materials or landform morphology, making radar imagery a valuable source of Quaternary geology information. To reduce the speckled appearance, which is typical of radar imagery, a median filter was applied. This filter has the combined effect of producing a smoother image while at the same time preserving edges and apparent contacts (Fig. 9).

A SPOT Panchromatic scene of acquisition date, June 4, 1985, was selected for this study. SPOT Panchromatic is a single band at 10-m spatial resolution that spans the green, red and near infra-red portions of the spectrum, similar to black and white infra-red photography. The choice of the image acquisition date was to correspond to a near vegetation-free surface, allowing for observation of the bare soil surface in the agricultural areas. In this scene, contrasts in soil moisture conditions, representative of different material types and textures, can be observed. These same observations would not have been possible within weeks of this acquisition date, as the agricultural crops in this area would have fully emerged. To enhance visually the spatial characteristics of this image, a sharpening filter (high pass) was applied (Fig. 10).

The digital terrain data for the test site was contained in 12 separate 1:10 000 5-m contour Ontario Base Maps (OBM). For the purpose of this study, this contour information was brought to a single vector data base. Through several GIS processing steps, this vector data base was interpolated and rasterized at a 10-m grid cell to provide a Digital Terrain Model (DTM; Fig. 11). With the elevation data in raster format, it was then transferred to an Image Analysis System (IAS) where image enhancement techniques could be applied. The most effective terrain enhancement method was found to be a shaded relief representation of the surface. This technique is usually associated with airborne geophysical data, but is equally effective on DTMs. Of the many views evaluated, the most informative for Quaternary terrain information was found to be at a sun azimuth of 53°, a sun elevation of 26°, and a vertical exaggeration of 3 (Fig. 12). To further enhance this image, a smoothing filter (low pass) was applied. It was found that the application of this filter gave the terrain surface a more realistic appearance.

The processing steps described in the previous section have preconditioned the images, such that when they are produced in composite these same features can be interpreted with much greater ease.

Various arithmetic combinations of the three images were evaluated for their usefulness in surficial and terrain mapping. The most useful composite was found to be a weighted average of the three images (Fig. 13). The weights applied to each image were 0.25 for both the SPOT Panchromatic and ERS-1 images, and 0.5 for the digital elevation data. The benefits of viewing the imagery synergistically can be seen in the final composite (Fig. 13). Some of the recognizable features include drumlins and drumlinoid features, a till plain, an area of hummocky disintegration moraine, a subaqueous fan, numerous kames and kettles, a subaqueous esker complex, and several paleo ice-marginal positions. This map and others are currently being evaluated and integrated into an Ontario Geological Survey-Geological Survey of Canada mapping program on the Oak Ridges Moraine. These products, will be used to assist in the revision of the current geology map (Fig. 3).

Digital Terrain Models for Extracting Terrain Features

In the previous example, we saw how a DTM can be used in a qualitative manner, where it can be treated as an image product, and enhanced, integrated and interpreted with other image products. In this example, we will examine how the same DTM (Fig. 11) can be used quantitatively in a raster GIS environment to extract the terrain parameter of slope and to delineate individual watersheds. By knowing the elevation of every pixel in an image, it is a simple calculation to generate the slope of the terrain at each pixel in the image. Figure 14 is a thematic representation of slope derived from the DTM in three-degree increments for the study area. Similar operations can also provide slope aspect and slope length.

A further application using a DTM is the delineation of watersheds or subwatersheds. Of the many algorithms that exist for watershed calculation, one of the most refined, and the method used in this study, is that developed by the United States Geological Survey (Jensen and Dominique, 1988). This program uses the raw DTM as input and, through a series of processing steps, generates an expected drainage network for the given terrain. This program can then calculate the individual drainage basins for user-specified or system-selected tributaries. Figure 15 is a sample output from this program. Seven major streams were manually seeded at the image edges: Duffins Creek, Reesor Creek, Little Rough Creek, Black Creek, Uxbridge Brook, West Duffins Creek, and Pefferlaw Brook. In this image, it is interesting to note not only the delineation of the individual basins, but also a north/south divide where the northern-flowing basins (Pefferlaw, Black and Uxbridge) contact the southern-flowing basins (Reesor, Little Rough, and Duffins). As many environmental geoscience projects are completed on a watershed basis, the ability to clearly define the basin can be essential (*e.g.*, Gerber and Howard, in press).

Raster GIS Modelling

This example will use the information generated from the previous examples to examine the relationship between the

ERS-1 radar image (Fig. 9) and the mapped Quaternary geology (Fig. 3). As stated previously, radar backscatter can be a function of many ground variables, including topographic relief, landcover, groundcover, surface roughness, and soil moisture. Each of these parameters can have a direct or indirect relationship with Quaternary materials or landform morphology, but to understand the contribution of each is difficult. In this example, we will attempt to isolate those areas where one of the parameters, soil moisture, is believed to be the dominant backscatter parameter, and then use these areas to examine the relationship between radar backscatter and Quaternary sediments. The only areas where soil moisture is the dominant radar backscatter parameter in the spring of the year are thought to be in the agricultural, flat areas.

As seen previously, there is a full range of glacially derived surficial materials present in the test site. They range from very fine-grained, low-permeability glaciolacustrine clays and tills to very coarse-grained, high-permeability, glaciofluvial and ice-contact sediments (Fig. 3). An advantage of using a spring ERS-1 scene (May 8, 1992), is that the ground has already thawed, and the

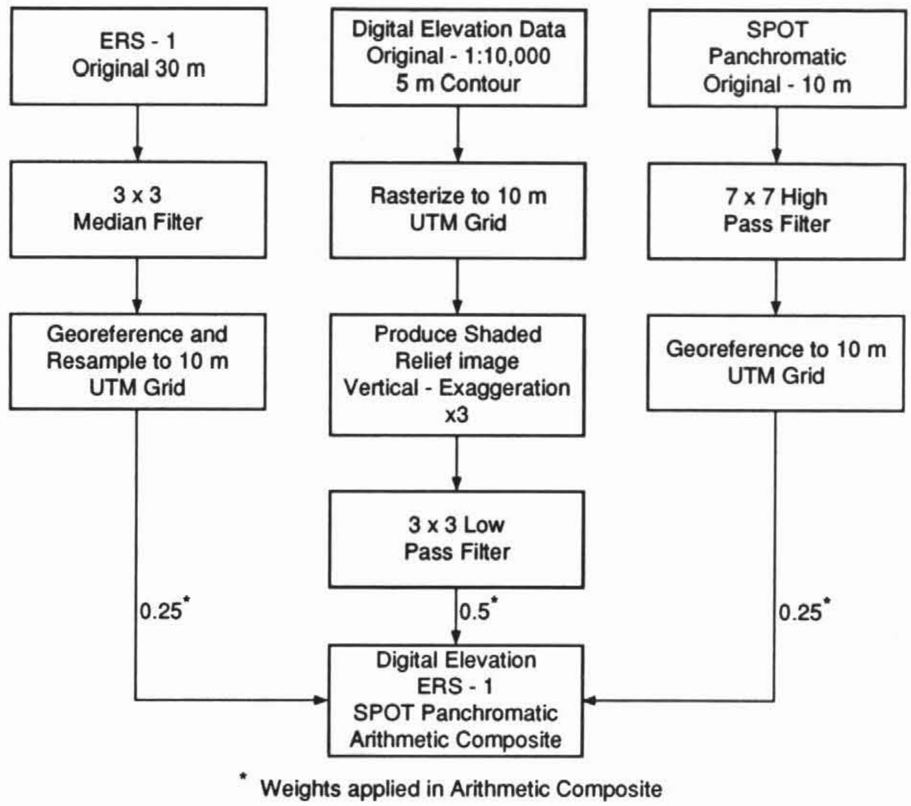

Figure 8 *Flow chart of image enhancement and integration methodology.*

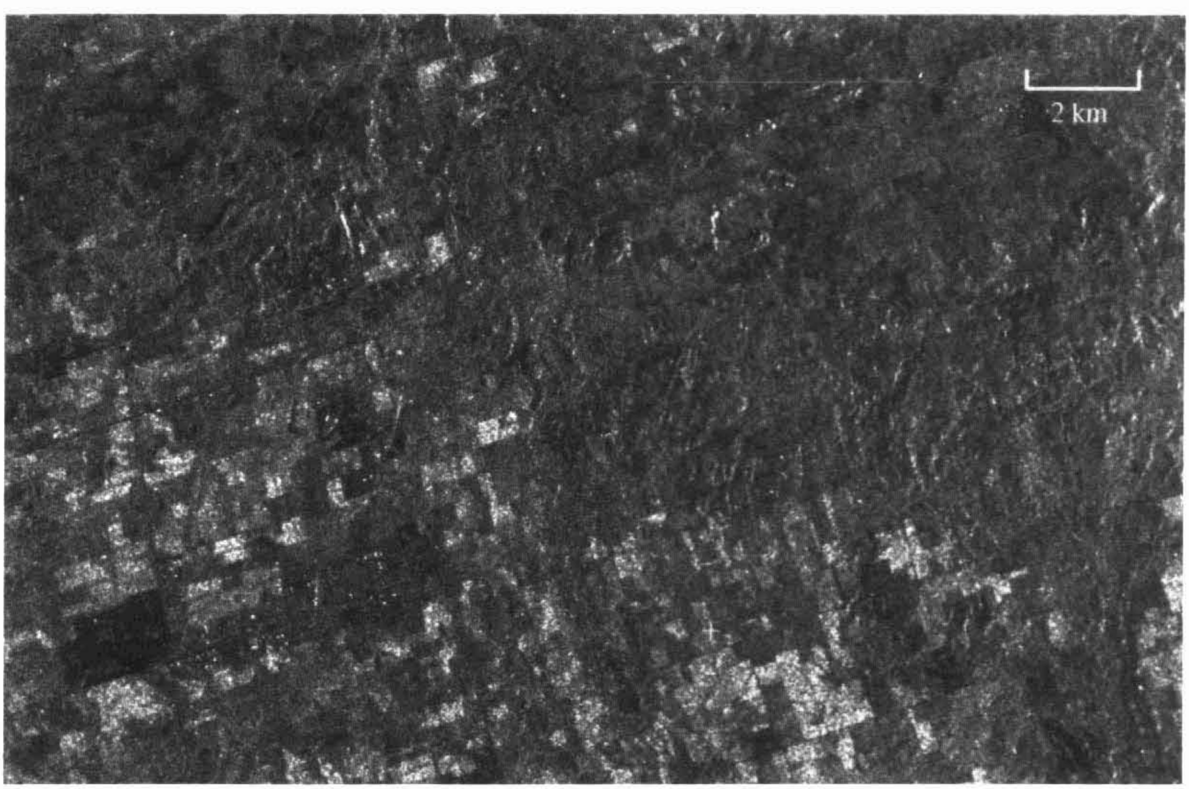

Figure 9 *Decimated, geometrically corrected ERS-1 satellite image of the study area.*

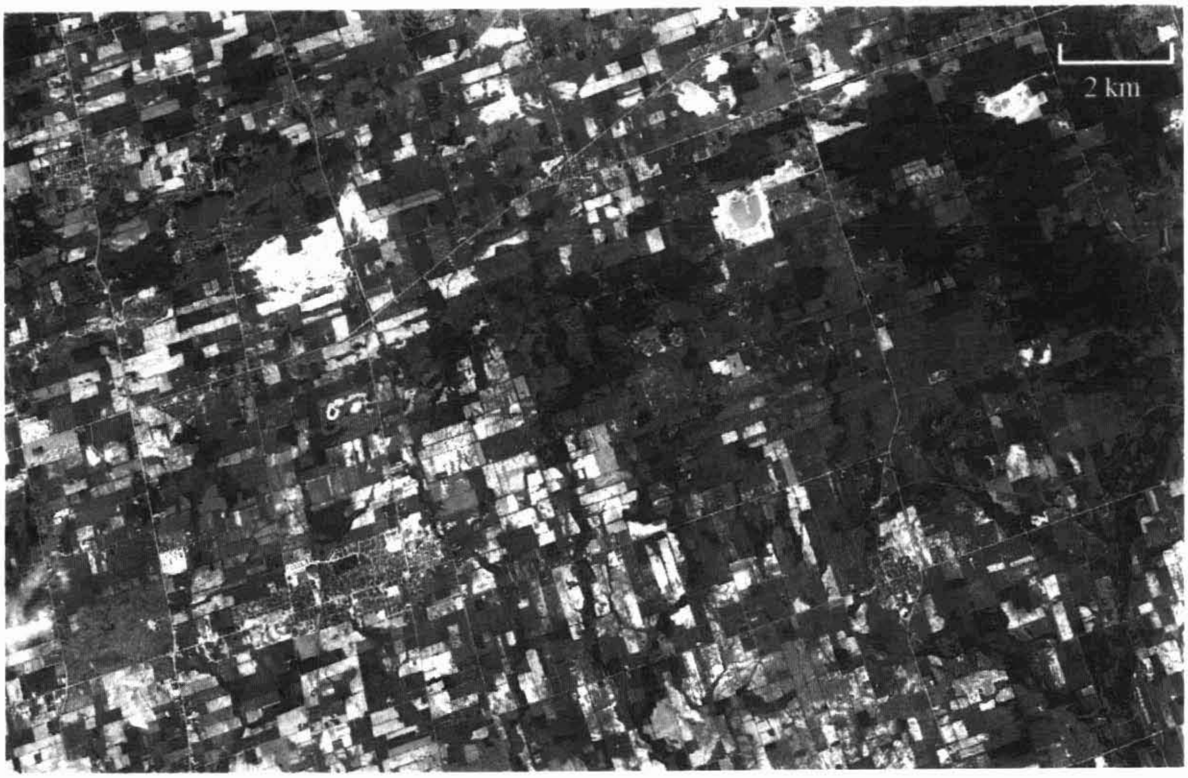

Figure 10 *Decimated, geometrically corrected SPOT Panchromatic image of the study area.*

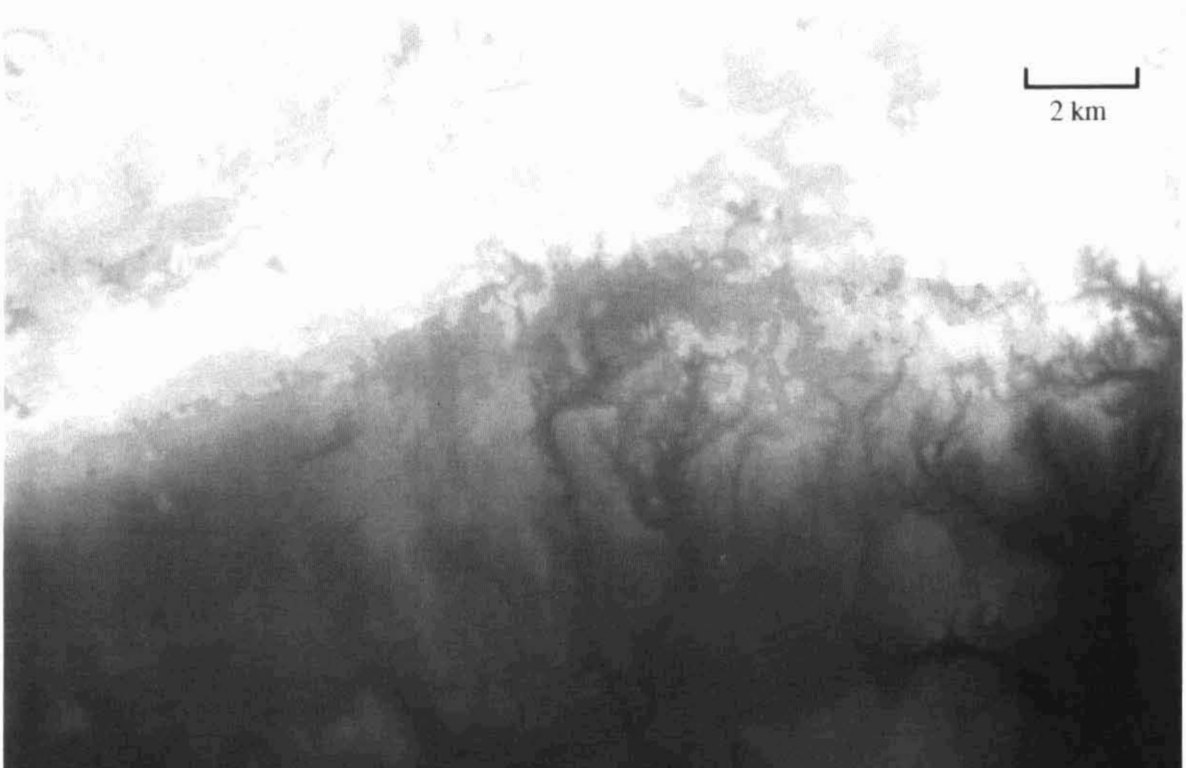

Figure 11 *Decimated, Digital Terrain Model of the study area.*

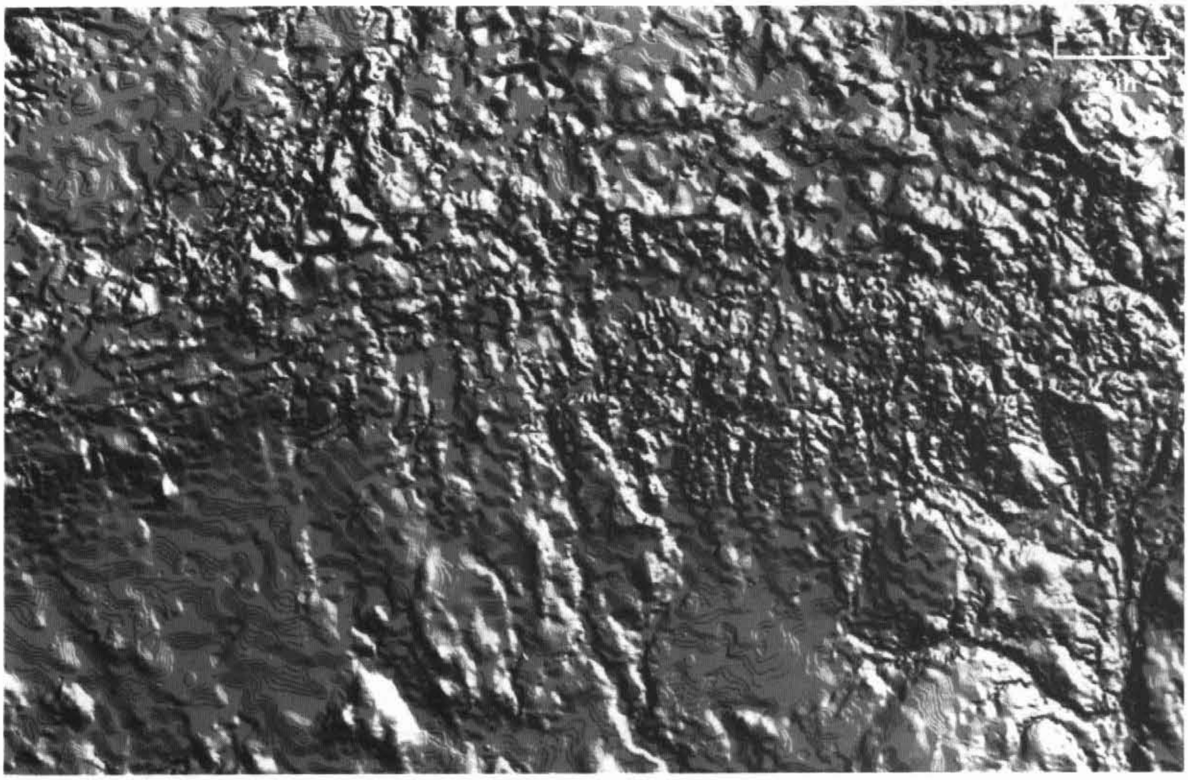

Figure 12 *Shaded relief enhancement of Digital Terrain Model.*

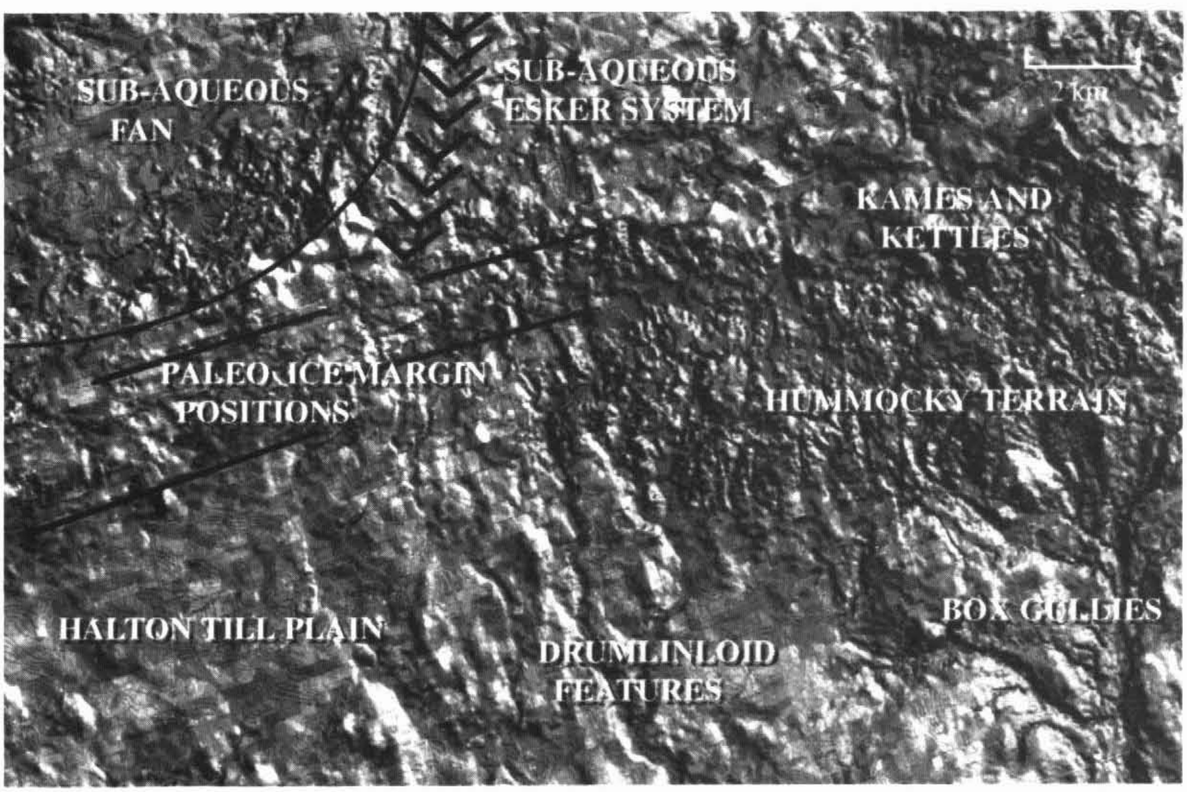

Figure 13 *Interpreted, decimated, arithmetic composite image of ERS-1, SPOT and DTM.*

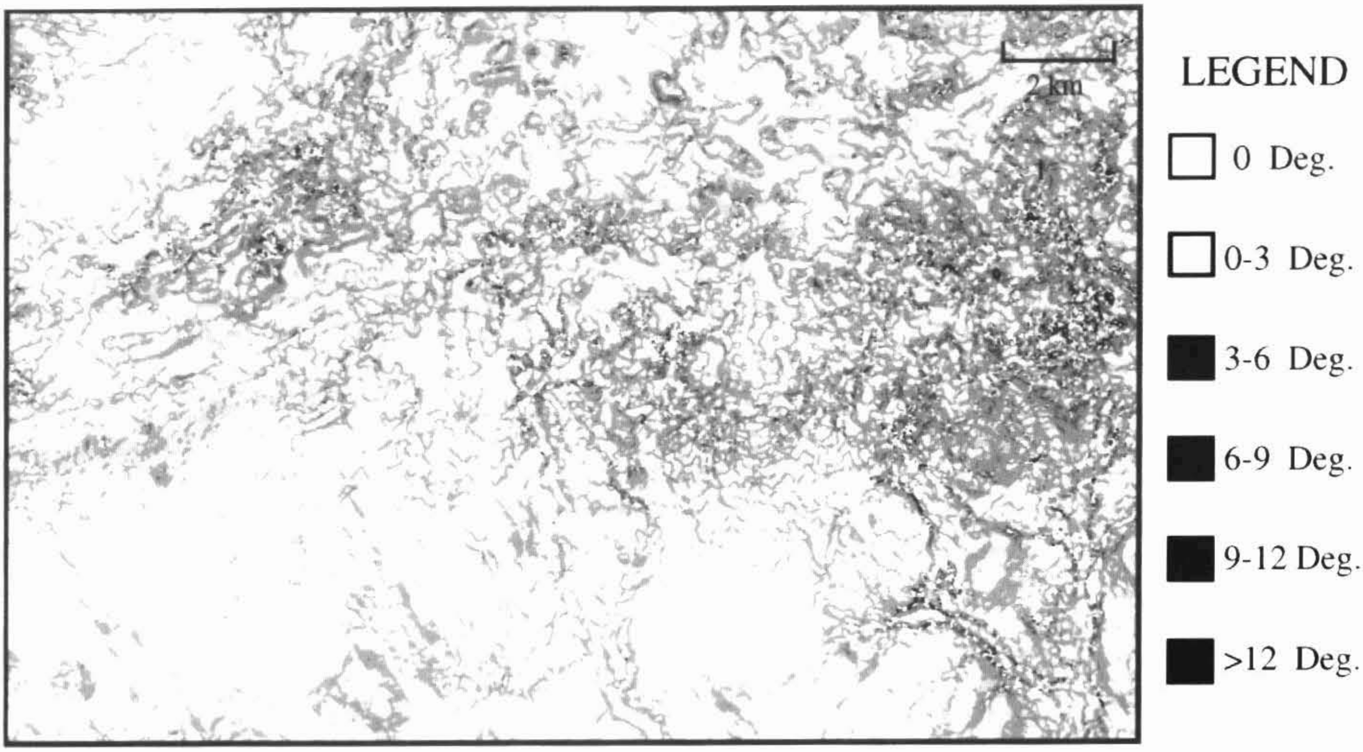

Figure 14 *Slope map of study area.*

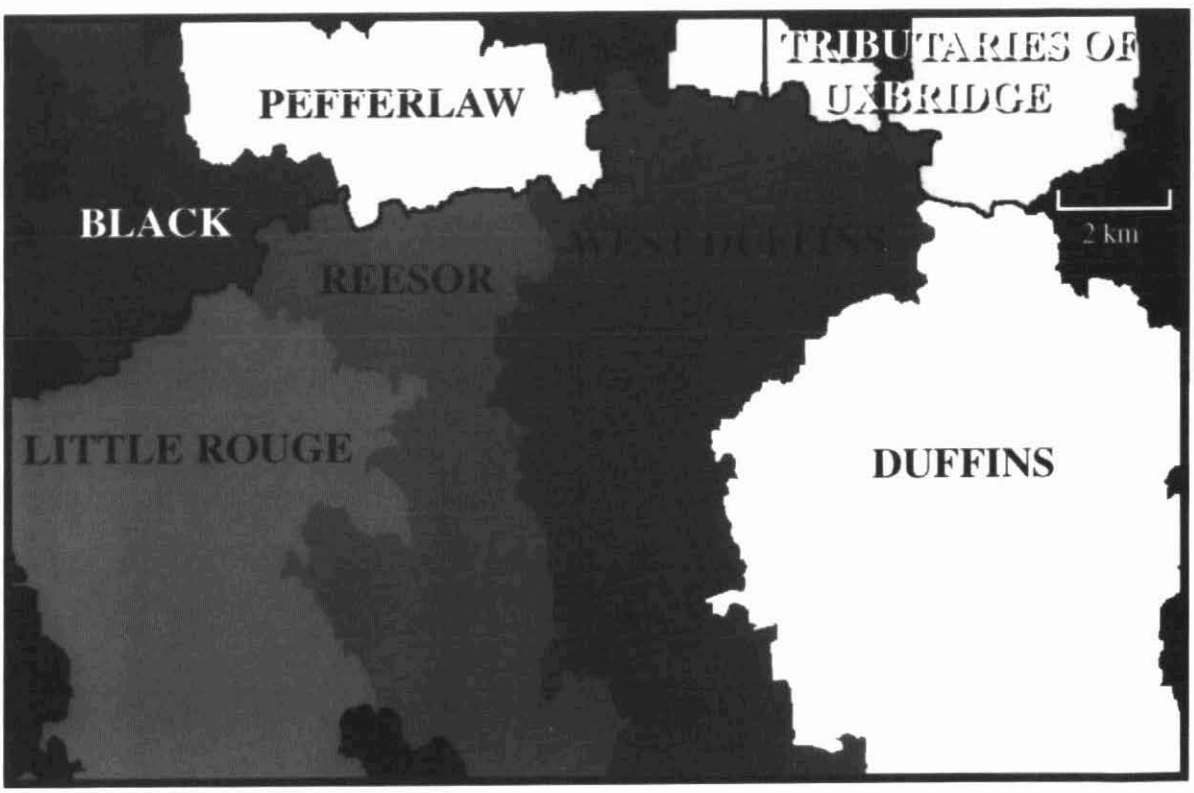

Figure 15 *Watersheds of the study area (see also Gerber and Howard, in press).*

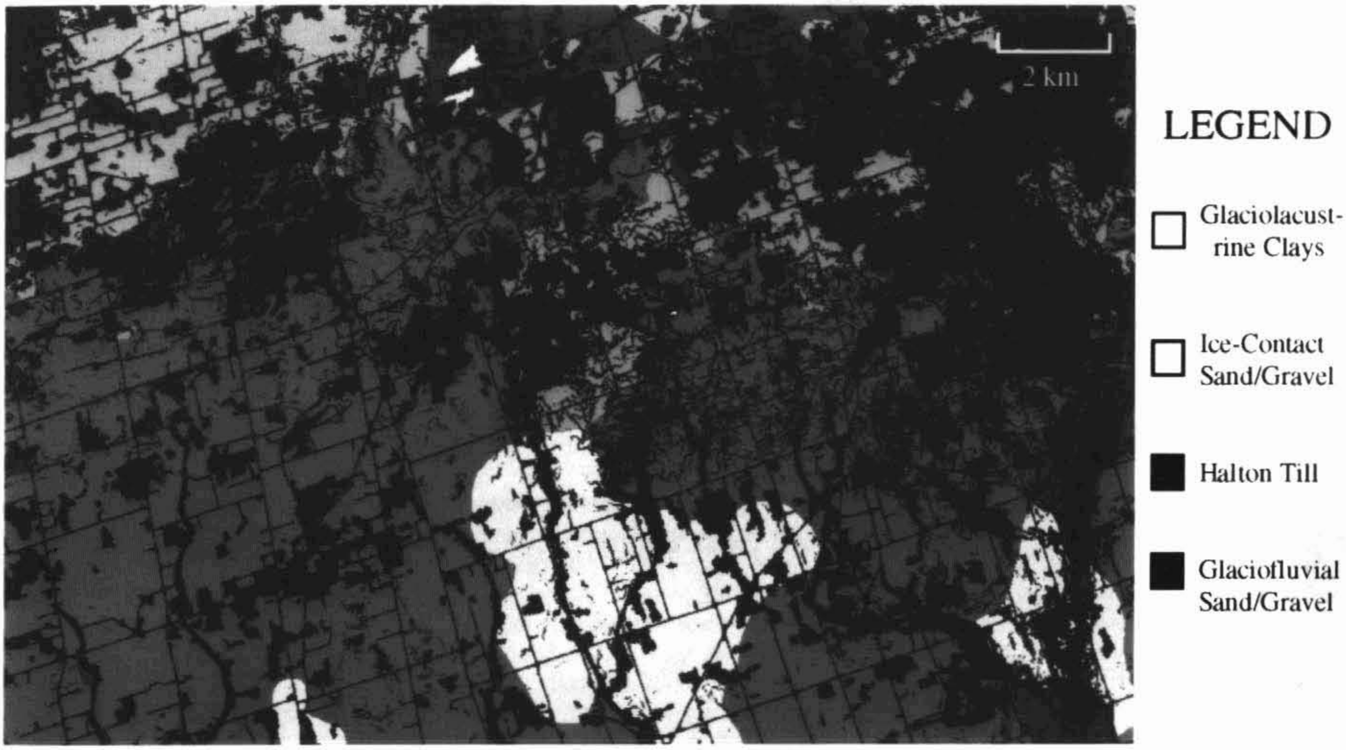

Figure 16 *Quaternary geology masks for the study area.*

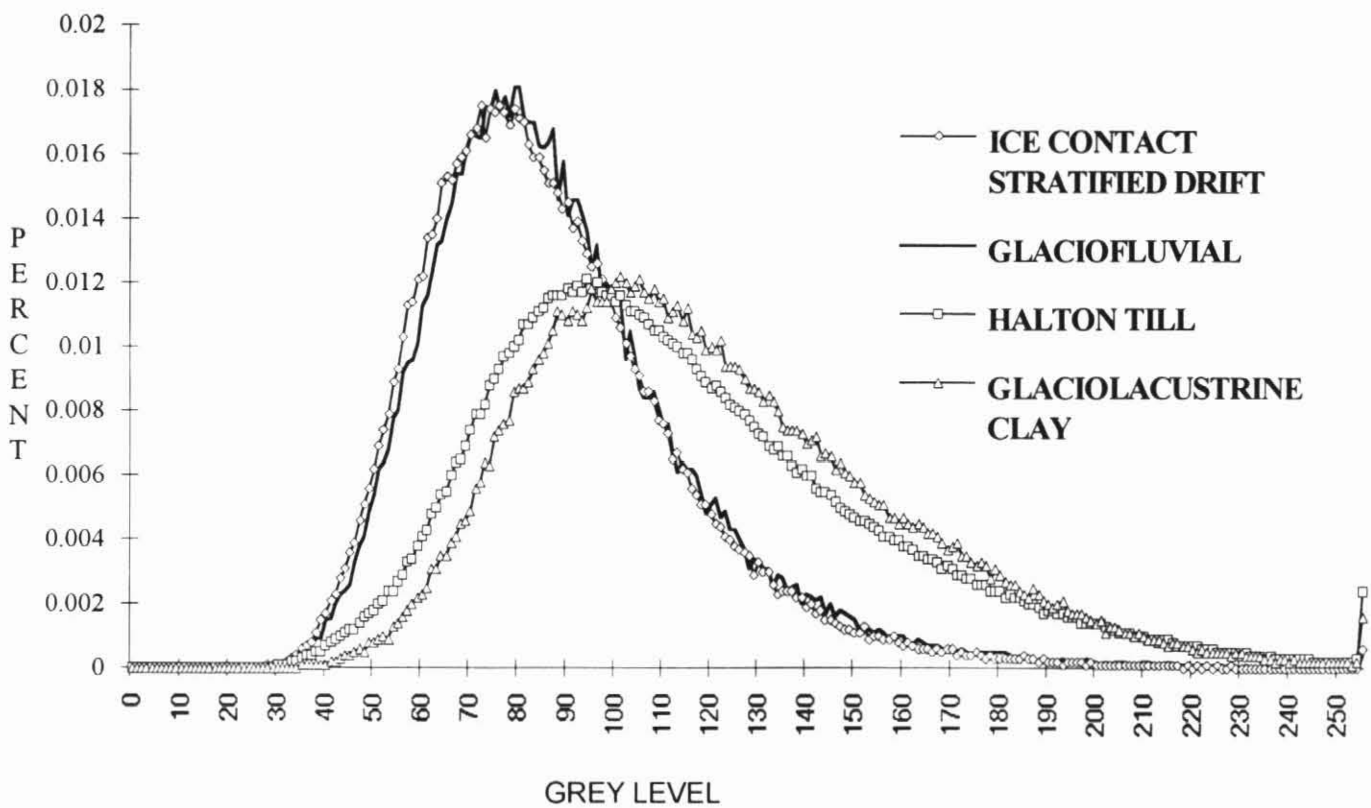

Figure 17 *ERS-1 radar signatures under masks used to construct Figure 16.*

winter accumulation of snow and ice has entered the ground-water flow system. Contrasts in surface soil moisture, at this time of year, are at or near maximum, and can often be related to the textural properties of the surficial materials. Another advantage of using spring imagery is that many of the agricultural areas are bare of crops and crop residues, which permits direct observation of the surficial materials without the influence of ground or land cover.

By using a raster-based Geographic Information System, the agricultural flat areas were delineated for each of the four major geological material types present in the study area (Fig. 16). The information necessary to delineate these areas was obtained from the geology map (Fig. 3), the land cover map (Fig. 7), and the slope map (Fig. 14). These four areas were then used as masks, under which ERS-1 statistics were calculated for the four major geological materials (Fig. 17).

The various surficial materials have distinct, near gaussian ERS-1 signatures (Fig. 17). The well-drained, drier, coarser-grained materials, such as the glaciofluvial and ice-contact deposits, as expected, have a lower radar response. The signatures of these two sediments are almost overlapping. This was to be expected as the difference between these two mapped units is based on their origins, and they, in fact, have a similar composition and similar hydrogeologic properties. The finer-grained materials, such as the Halton Till and glaciolacustrine deposits, exhibit a much stronger radar signal. These low-permeability materials are still quite wet, and this is evident in the radar signatures. One would expect these materials to have similar hydrogeological responses. This is seen in the signatures. The radar curves are very similar in shape, but the glaciolacustrine clay has a slightly brighter shift. This difference can be attributed to the glaciolacustrine clays having a slightly lower permeability and, therefore, being wetter than the Halton Till. These early results demonstrate the potential use of satellite radar imagery for ground-water studies, in addition to its use as a Quaternary geological mapping tool.

DISCUSSION

This paper demonstrates only a few of the spatial data analytical capabilities that are now possible with current digital data bases and new spatial data analysis software products. There are several other technological trends in the geomatics sector occurring concurrently that will also have a significant impact on the environmental geosciences.

Advances in raster scanners are presenting new ways of viewing traditionally used spatial data. Digital raster scanners have developed to the point where they can fully capture the information content of photographs or photographic negatives. Systems have been developed that enable an interpreter to view, interpret and annotate aerial photographs stereoscopically on screen. Software also exists that can geometrically correct aerial photographs and annotated interpretations for camera lens and terrain distortions. These developments bring aerial photographs and aerial photograph interpretation into the digital realm, where a full suite of image analysis and GIS functions can be applied to the imagery.

The availability of spatially referenced data is rapidly increasing. Where once the public would purchase hardcopy maps, government agencies are now distributing their data in both hardcopy and digital format. By the late 1990s, there will be a dramatic increase in the quality and quantity of specialized satellite imagery, and this imagery will be easily accessible in a more competitive market. There are now advanced satellite sensors being developed in the visible, reflected infra-red, thermal infrared, and microwave spectral regions. Some of these sensors will have a spatial resolution of down to one metre. One of the largest beneficiaries of this imagery will be the environmental sciences. NASA's recently announced Smallsat satellites are expected to be launched before 1997. One of these satellites will provide a panchromatic channel at 3-m spatial resolution and be capable of stereo imaging. The other Smallsat will be a hyperspectral imaging satellite recording 30-m resolution images on 384 spectral bands ranging from 0.4 microns to 2.5 microns (visible to reflected infra-red). To promote the use of this data, NASA plans to offer this imagery free of charge for the first year after launch. Three private American companies, Lockheed, WorldView and Orbital Sciences, have also announced plans to initiate their own satellite programs, and expect to be marketing specialized satellite imagery within the next few years.

A joint American-Japanese program is now developing an advanced resource satellite thermal sensor, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer). The multi-spectral thermal infra-red imagery from ASTER will provide a thermal picture of the Earth we have not seen before. Similarly, the Canadian RADARSAT satellite, launched in 1995, will provide the most advanced radar imagery of the planet yet available. In addition to these new programs, imagery from Russian and Indian satellites is now being marketed internationally.

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