Digital Elevation Models in environmental geoscience, Oak Ridges Moraine, southern Ontario[1]

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Abstract: Knowledge of topography is often a basic requirement for studies undertaken in the natural sciences, specifically, geomorphology, hydrology, and geology. Digital Elevation Models (DEM) can be developed using Geographical Information Systems and digitally structured topographic maps to provide contiguous information of a landscape. Once terrain information is captured as a DEM, the potential for multidisciplinary geoscience applications increases dramatically.

A 1:10 000 scale DEM was constructed and used to develop integrated image analysis techniques for geological and landform mapping within a 15 by 20 km test site of the Oak Ridges Moraine. The techniques developed in the test area are being applied on a 1:50 000 scale DEM that includes the entire Greater Toronto Area. Examples of DEM applications are provided from both the test site and regional models. The DEM is also being used by geologists on desktop PC systems as an aid in geological mapping.

Résumé : La connaissance de la topograhie est souvent une exigence de base pour les études entreprises dans les divers domaines des sciences naturelles, en particulier en géomorphologie, en hydrologie et en géologie. Des modèles altimétriques numériques (MAN) peuvent être conçus en faisant appel aux systèmes d'information géographiques et aux cartes topographiques numérisées pour obtenir les informations sur tous les secteurs contigus d'un paysage. Lorsque des informations sur un terrain sont intégrées sous la forme d'un MAN, les possibilités d'application multidisciplinaire en sciences de la Terre s'accroissent à un rythme fulgurant.

Un MAN à l'échelle de 1:10 000 a été produit et utilisé pour élaborer des techniques d'analyse d'images intégrées; le but consistait à établir des cartes (géologie et formes du relief) d'un site d'essai de 15 kilomètres sur 20 kilomètres de la moraine d'Oak Ridges. Les techniques mises au point dans la zone d'essai sont actuellement appliquées dans l'élaboration d'un MAN à une échelle de 1:50 000 qui englobe l'ensemble de la région du Toronto métropolitain. Des exemples d'applications de MAN sont donnés tant dans le cas du site d'essai que dans celui de modèles régionaux. Les géologues se servent également des MAN sur des ordinateurs portatifs en tant qu'outil de cartographie géologique.

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INTRODUCTION

An essential component of the GSC NATMAP (NATional MApping Program) and Hydrogeology projects is digital data integration within a Geographic Information System (GIS). To achieve this objective the Oak Ridges Moraine project has developed a multicomponent database (Russell et al., 1996). A key element of this data set is the digital topographic bases and associated anthropogenic layers. The Oak Ridges Moraine (ORM) project is completing surface and subsurface geological mapping in the Greater Toronto Area. Traditionally, this type of mapping has been compiled through airphoto interpretation and field verification. Remote sensing and GIS technologies provide an additional approach and opportunities for streamlining and automating some aspects of the mapping process. Surfical geology mapping is comprised of two components, landform analysis and sediment texture mapping. Remote sensing and GIS techniques can be used to perform both these tasks. Digital Elevation Models (DEM) are suitable for landform analysis, while remote sensing imagery can provide information on both sediment textures and landform elements (Kenny et al., 1994; Kenny and Barnett, in press). With carefully selected image analysis techniques, multispectral imagery can be enhanced to identify specific elements of geological interest.

The Oak Ridges Moraine project, through collaboration with the Ontario Provincial Remote Sensing Office (PRSO) within the Ontario Ministry of Natural Resources (MNR), are integrating both remote sensing imagery (Landsat TM, SPOT, ERS-1, RADARSAT) and DEM for surface mapping and hydrogeology investigations. This paper outlines several examples of the use of DEM to environmental geosciences.

STUDY AREA

The Oak Ridges Moraine area project is mapping the surface and subsurface geology within nine 1:50 000 NTS map sheets north of Lake Ontario (Fig. 1). The study area is centred on the Oak Ridges Moraine, a 150 km long east-trending landform. This moraine is one of several prominent glaciofluvial-glaciolacustrine moraines in southern Ontario (cf. Barnett et al., 1991; Fulton, 1995). The study area is predominantly composed of glacial sediments which reach a thickness of up to 200 m. The stratigraphy is complex with sediments having been deposited during a succession of glacial events and with major erosional events incising older deposits (Sharpe et al., 1994, 1996). The surface sediments and landforms of the area record a complex series of events related to the erosional and the depositional history of the area. In some areas surface landforms may be controlled or influenced by subsurface features.

METHODOLOGY

Background

With the introduction of digital topographic maps covering broad areas of Canada, such as the Ontario Base Maps and the National Topographic Series, and the wide availability of GIS, the ability to create and use DEM for numerous geoscience applications has increased dramatically. As GIS and DEM move onto geoscientists' desktops, they are providing new opportunities for viewing and analyzing data. Satellite and airborne digital stereo imaging technology is advancing rapidly, as are the automated DEM extraction algorithms that use these data, but until these technologies become fully operational and cost effective, the best source of DEM will be from structured topographic maps.

There has been a constant refinement in the methods used to generate DEM from topographic maps and the tools used to analyze them. Some earlier DEM programs used only contour and point elevation data to interpolate a terrain surface which usually resulted in significant differences between the generated surface and the actual terrain surface. Many improvements to these early models have been developed and can be grouped broadly into two categories: drainage enforcement techniques and improved interpolation methods.

A major improvement in developing DEM is the incorporation of the digitally mapped drainage network into the model generation process, ensuring that streams and rivers represent local minima in the DEM. This process was improved by using drainage enforcement procedures on the drainage network to create 'hydrologically sound' DEM (Hutchison, 1989, 1993). The process of drainage enforcement

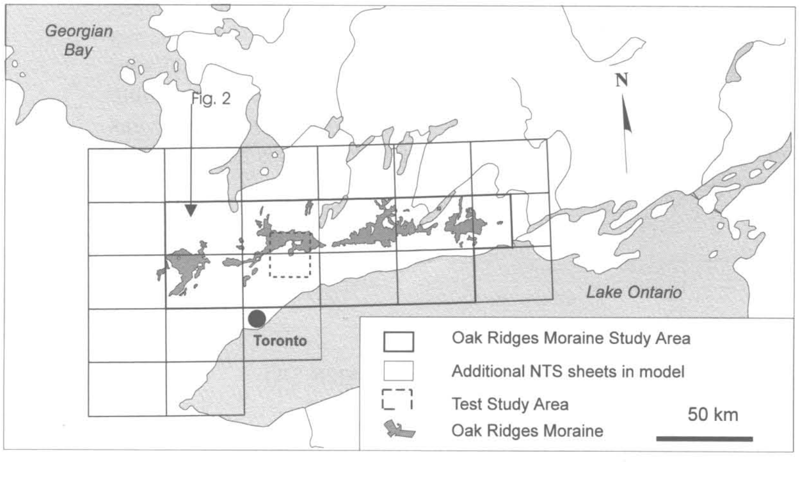

Figure 1.

Location map of the study area and area covered by the respective DEM models.

ensures the continuous downslope flow direction for all connected drainage networks to the extent of altering original point and contour elevation data to conform to drainage conditions. Recognizing that closed drainage networks are relatively rare in a natural terrain, the drainage enforcement process attempts to automatically remove, subject to user-specified tolerances, closed drainage from the DEM. With properly selected tolerances, true closed drainage conditions such as occur in areas of kettle lakes and karstic terrain can exist in the final DEM. The use of drainage networks as enforcement in the DEM generation process often requires a significant effort in restructuring and ensuring the accuracy of the drainage network.

The second largest area of improvement in DEM generation has been in the interpolation algorithms used to generate the models. Early DEM did not sufficiently represent ridge and valley lines as distinct breaks in the terrain. In elevation contour data, the location of valleys and ridge lines can be identified as points of local maximum curvature in the contours. By connecting such points between contours lines, both valley and ridge lines can be delineated automatically and used in generating DEM (Hutchison, 1989, 1993) to produce a much more realistic and informative terrain surface. These new developments in generating DEM are being used more frequently as software packages such as Arc/Info TOPOGRID and ANUDEM become available.

Once elevation data is in a digital raster format, such as a DEM, it can be treated as an image product, where image enhancement and image integration techniques can be applied (Harris et al., 1994). Common viewing enhancements for DEM include hillshading, perspective hillshading, and perspective mesh net or wireframe. Alternatively, other data sets or images can be draped on the DEM to provide a visual representation of the relationship between a secondary attribute (ie. geology, Landsat TM imagery) and topography. The DEM can also be integrated with other image products to produce stereo-imagery for analysis using either traditional stereo or digital techniques (Toutin and Rivard, 1995).

At a cursory level, interpretation of DEM surfaces relies on similar techniques as applied in airphoto interpretation, such as, assessment of surface roughness, linearity, form, spatial associations, and elevation relationships. More sophisticated analysis can be applied using mathematical morphological operators to enhance or minimize specific features (Bonham-Carter, 1994). As well the information derived using such methods can be used with other geo-referenced data sets in knowledge-based models (Srinivasan and Richards, 1993).

Model development

DEM have been developed at both the 1:10 000 and 1:50 000 scales by using the vector contour and point elevation data. The 1:10 000 model has been built using twelve, 5 m contour interval Ontario Base Maps (OBM). The 1:50 000 model presently consists of eleven NTS map sheets, with an original 10 m contour interval (Skinner and Moore, 1996). The model is presently being enlarged to 23 sheets (Fig. 1). Both models have been developed using similar interpolation techniques: contour-to-point, point-to-Triangulated Irregular Network (TIN), TIN-to-lattice, and lattice-to-Grid. The elevation data was then interpolated and grided at horizontal resolutions of 10 and 30 m for the 1:10 000 and 1:50 000 DEM respectively. A 30 m grid scale was used as this matches the resolution of TM imagery being used within the study. At the 1:50 000 scale, the major streams and lakes were incorporated. Drainage enforcement and some of the newer interpolation techniques have not yet been used on the present DEM, which make them inadequate for hydrological modelling. To use the NTS drainage network in the 1:50 000 scale DEM generation process, it must first be restructured to ensure that it is contiguous. Vector segments must be properly positioned and orientated in a downslope direction, and double line rivers replaced by single line segments. The process of restructuring the drainage network has, to a large degree, been automated by the use of recently developed macros (Paquette, 1996). The final DEM will be constructed using full drainage enforcement techniques available in ArcInfo TOPOGRID and as a result will be hydrologically sound. To assist in this task and to provide an added level of quality control, a Landsat Thematic Mapper (TM) image, georeferenced at 1:50 000 scale, and Ontario Base Map drainage are being used as backdrops. Where discrepancies between the NTS and other networks are encountered they will be investigated and corrected. This process is necessary as field mapping has identified discrepancies between the published NTS mapsheets, NTS digital files, and present stream courses.

There has not been an assessment of the accuracies of the models generated to date. For qualitative terrain mapping, accuracy is not a major issue, but for quantitative applications, including hydrological modelling an accuracy assessment of the model will be essential. Surface verification of the final model will be achieved by the integration of geodetic benchmark information available across the study area. An attempt will be made to follow United States Geological Survey (USGS) protocol, where for 7.5 minute DEM, 28 test points are selected and compared with the geodetic benchmarks (United States Geological Survey, 1990).

An additional source of terrain information, fifteen 1:25 000 scale digital lake bathymetric field sheets have been ordered from the Canadian Hydrographic Survey for portions of Lake Ontario, Lake Simcoe, Lake Scugog, and Rice Lake. These bathymetric data will be used to generate an offshore DEM which will be incorporated with the onshore DEM to provide an integrated model.

GEOSCIENCE APPLICATIONS

DEM have been applied to terrain mapping since the early 1970s (Collins, 1975). The lack of widespread use has resulted from problems associated with the generation and viewing of models which required extensive computing power and operator expertise. Desktop GIS systems now enable geologists to create and view DEM on PC systems (PCI Terrain Analysis, Spans Explorer, MapInfo/Vertical Mapper) and assorted shareware software (Microdem). The project has four principal applications for the DEM within the surface-subsurface mapping and hydrogeology program: a) regional datum, b) terrain mapping, c) DEM and satellite image integration, and d) watershed and drainage analysis.

a) Regional datum

For the Oak Ridges Moraine project an extensive database derived from many sources has been developed (Russell et al., 1996). The elevation control on this data has been assigned from a variety of sources and in places is erroneous. As the project is interested in analyzing subsurface data with respect to depth from surface or elevation above sea level, it is necessary to have a unique project elevation datum. The DEM will provide an important role as a means of assigning new elevation control to all the data being used by the project. In addition, the projects largest subsurface data set, the Ministry of Environment and Energy waterwells, has approximately 20 to 25% location errors (G. Hunter, pers. comm., 1994). A systematic process of identifying these errors has been developed using the Ontario Base Map lot and concession fabric and elevation control (Hunter, 1996). The project anticipates comparing the DEM and waterwell elevations as a method of location error checking during a second round of verification.

b) Terrain mapping

The DEM can serve a number of functions in terrain mapping, and this role can be optimized by image enhancement and visualization techniques. Here we present three enhancements of the DEM data; hillshaded, perspective shaded relief, and filtered perspective shaded relief as a basic illustration of the power and versatility of working with elevation data in a DEM format.

From the regional 1:50 000 scale DEM a hillshaded representation is presented for the Alliston (31D/4) mapsheet (Fig. 2). This image has been generated by sampling the regional 30 m grid cell Oak Ridges Moraine DEM at a reduced resolution of 100 m spacing. This example highlights the flexibility available to geologists for regional terrain analysis. While lacking the resolution of 1:50 000 airphotos traditionally

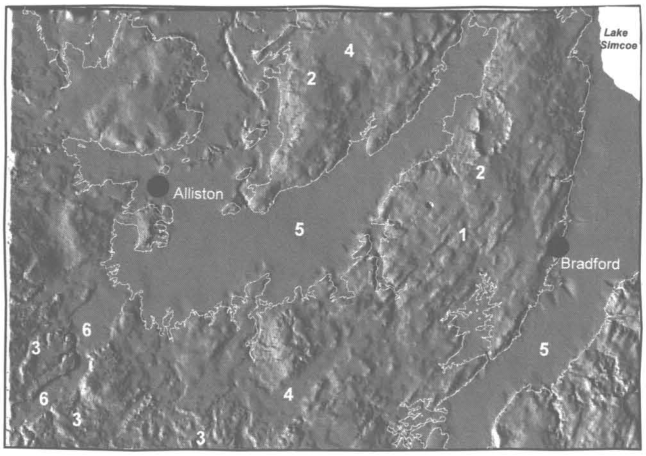

Figure 2.

A shaded relief DEM of the Alliston NTS map sheet showing a general visual classification.

Table 1. Classification table for Figure 2, indicating DEM characteristics and supplemental data layers used to assign surface classifications.

Label	Topographic character	Supplemental information from drainage & anthropogenic layers	Interpretation
6	incised, smooth	drainage layer, air photos	paleofluvial system
5	smooth, tight elevation range, below 230m	contour overlay	Lake Algonquin bottom sediments
4	smooth, elevation,		lacustrine silts
3	roughness, incoherent, elevation	mapped sand and gravel pits	ORM sands
2	elevation, roughness	mapped sand and gravel pits	sand & gravel
1	streamlined, roughness, elevation		till surface

used for regional synthesis, it provides distinct advantages of economy of time, ability to integrate or overlay other data sets, ease of topographic analyses, and optimizing advantages offered by other viewing combinations (rotation, shaded relief, vertical exaggeration, scale changes). In this example a visual analysis permits the identification of several terrain categories (Table 1). Identification of some elements has been aided by drainage and anthropogenic layers from the digital topographic bases.

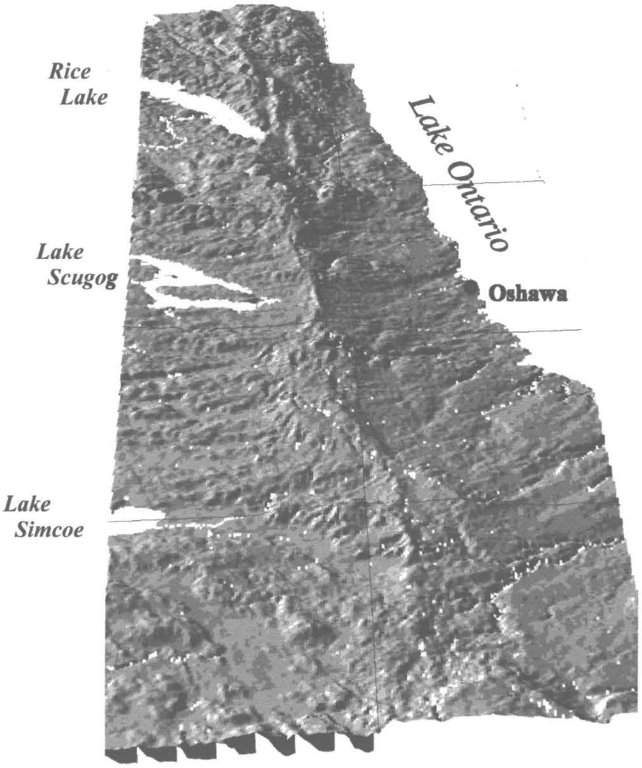

Figure 3. A shaded relief perspective view (west to east of Whole ORM) of the 1:50 000 scale Oak Ridges Moraine DEM.

Perspective viewing of DEM can be an effective tool for conceptual understanding of landscape relationships. A shaded relief enhancement of the moraine, (observer 25°, altitude 30°, and distance 284 km, and a sun azimuth 25°, declination of 35°, and a vertical exaggeration 12 times (Fig. 3), highlights the strong linear form of the moraine, variations in moraine width, the variable nature of the moraine crest and variations in the elevation of the moraine crest along its length.

For surficial geology mapping, a shaded relief representation of the test area was found to be an effective interpretative aid. Illumination from the northeast, at an elevation of 26°, and a vertical exaggeration of three effectively displays several of the major terrain elements (Fig. 4). To further enhance terrain characteristics, a smoothing filter (3 x 3 neighbourhood low pass) gave the terrain surface a smoother, more realistic appearance. In this view, several of the major terrain elements and terrain features can be clearly delineated, including the Halton till plain, the streamlined features on the Halton till plain, an area of hummocky moraine, an area of kames, and a glaciofluvial outwash area (Fig. 4). Other views highlighted different terrain features for mapping; an illumination set from the southeast enhances the terrain transition between the hummocky terrain and glaciofluvial outwash deposits.

c) DEM and satellite image integration

For the test site, Landsat TM imagery was merged with a SPOT Panchromatic image. An image integration methodology was selected that best preserved the spectral characteristics of the Landsat imagery (6 spectral bands @ 28 m spatial resolution), while at the same time taking advantage of the high spatial resolution of the SPOT image (single and @ 10 m spatial resolution) (Chavez et al., 1991). A stereo pair

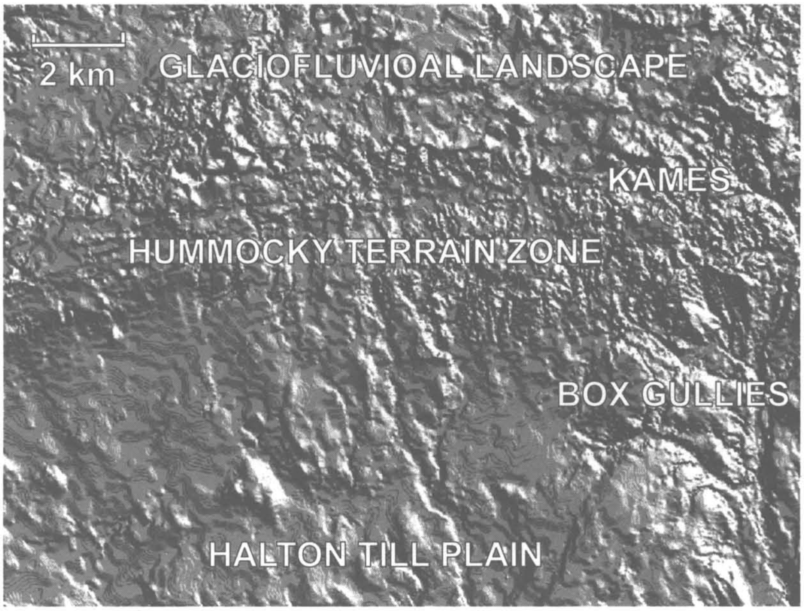

Figure 4.

Shaded relief enhancement of the test site 1:10 000 DEM with physiographic regions indicated.

was generated from the merged satellite imagery using the test site DEM (Fig. 5). This stereo-pair was generated by calculating a parallax for each pixel in the original image as a function of elevation, derived from the DEM, and a user supplied stereoscopic factor. For the processing of this image a stereoscopic factor of 15 was applied to produce the stereo effect. While such a stereoscopic factor produces a vertical exaggeration, it is not more than usually found in stereo aerial photography. Although these images are the result of several enhancements, merging techniques, and contain imagery from two different sensors and a DEM they are prepared for very traditional image/photo interpretation. A user with experience in interpreting multi-spectral imagery and stereo aerial photography can apply these skills directly on the merged imagery.

The stereo-pair shows a portion of the hummocky terrain zone at the northern margin of the Halton till plain. This hummocky terrain is a common element of moraine topography and can be delineated easily in such stereo-pairs. This hummocky terrain zone marks the most northerly advance of the Lake Ontario ice following formation of the Oak Ridges Moraine during the Late Wisconsinan.

d) Watershed and drainage analysis

A component of the hydrogeology field program is delineating the spatial distribution of groundwater discharge within watersheds by measuring stream baseflow at a number of stream locations (Hinton, in press). The net increase in stream discharge along stream segments is a measure of the groundwater discharge within each segment. The net discharge can be normalized to the length of the stream segments or to the contributing area of each stream segment (Fig. 6).

The final DEM will be used to facilitate both data presentation and analysis. The determination of stream length and drainage area requires the stream to be segmented and the subcatchment boundaries to be delineated for each flow gauging location. A hydrologically sound DEM generated using full drainage enforcement procedures will be used with existing subroutines to automate subcatchment delineation (Jenson and Dominique, 1988) and generate drainage networks based solely on terrain (Jenson and Dominique, 1988; Jensen, 1993). The DEM will also be useful for interpreting the survey results to help determine how geological and topographic factors may influence groundwater discharge. Using the DEM within a GIS, groundwater discharge along stream segments can be analyzed with respect to elevation, topographic slope, and surficial geology.

A common element of glacial landscapes are kettle lakes or hummocky moraine (Prest, 1983). In the Oak Ridges Moraine numerous kettle lakes and depressions are associated with parts of the moraine. Groundwater level measurements indicate that these landforms are frequently associated with groundwater recharge conditions. The DEM will be useful for automatically delineating kettle lakes and depressions which will aid the interpretation of regional groundwater flow

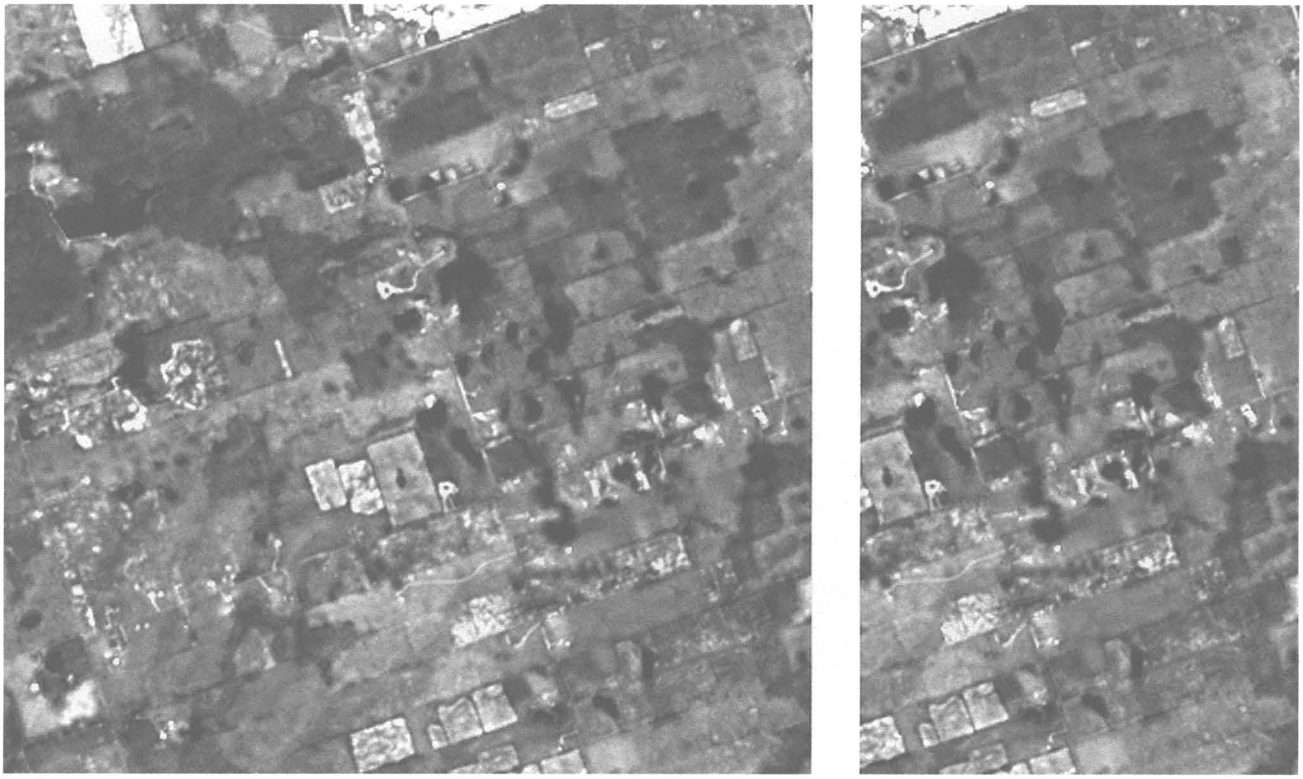

Figure 5. *Stereo-Pair showing hummocky terrain on the south central flank of the Oak Ridges Moraine. Imagery generated from merged Landsat TM, a SPOT Panchromatic image and a DEM.*

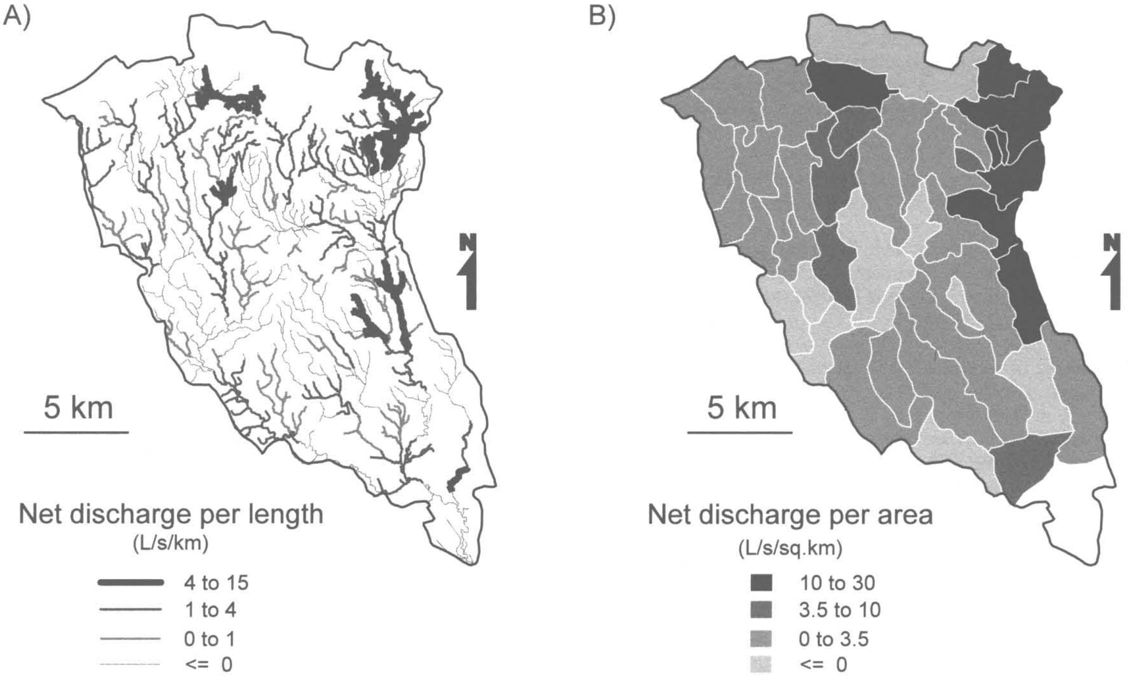

Figure 6. *Net baseflow discharge in the Duffins Creek watershed expressed with respect to **A)** stream length, and **B)** catchment area.*

conditions. Since drainage enforcement techniques may fill depressions, kettle lakes emphasize the importance of careful selection and application of DEM generation procedures.

CONCLUSIONS

Improvements in DEM generation procedures, PC hardware, and GIS and image analysis software are making the models more accurate and more accessible for multiple uses in environmental geoscience projects. Hydrologically sound DEM are being developed and tested for the Oak Ridges Moraine area of southern Ontario. These DEM will be particularly useful for several tasks including: 1) verifying georeferenced data, 2) automating various mapping procedures, 3) landform analysis, 4) integration with other imaging techniques, 5) topographic analysis of spatial data, and 6) data display and presentation.

Topographic maps are used as base maps for data presentation and analysis in geoscience projects. With the increased use and availability of GIS, digital databases, and digital maps in the geosciences, the digital representations of a topographic surface are becoming as important a tool as the topographic map.

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