

GIS Spatial Modeling of Landscape and Water Systems in GTA, Canada

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ABSTRACT

Modeling landscape with high-resolution digital elevation data (DEM) in a geographic information system can provide essential morphological and structural information for modeling surface processes such as geomorphologic process and water systems. This paper introduces several DEM-based spatial analysis processes applied to characterize spatial distribution and interactions of ground and surface water systems in the Great Toronto Area (GTA), Canada. The stream networks and drainage basin systems were derived from the DEM with 30-meter resolution and the regularities of the surface stream and drainage patterns were modeled from a statistical/multifractal point of view. Together with the elevation and slope of topography, other attributes defined from modeling the stream systems, and drainage networks were used to associate geological, hydrological and topographical features to water flow in river systems and the spatial locations of artisan aquifers in the study area. Stream flow data derived from the daily flow data recorded at river gauging stations for multi-year period were decomposed into “drainage-area dependent” and “drainage-area independent” flow components by two-step “frequency” and “spatial” analysis processes. The latter component was further demonstrated most likely due to the ground water discharge. An independent analysis was conducted to modeling the distribution of aquifers with information derived from the records of water wells. The focuses were given on quantification of the likelihood of ground water discharge to river and ponds through flowing wells, spring and seepages. It has been shown the Oak Ridges Moraine as a unique glacier deposit unit serves as a recharge layer and the aquifers in the ORM underlain by Hilton Tills and later deposits exposed near the steep slope zone of the ridges of ORM provide significant discharge to the surface water systems (river flow and ponds) through flowing well, springs and seepages.

Keywords: GIS, Drainage System, water flow, flowing wells, prediction.

1. Introduction

Understanding water systems (groundwater, surface water and precipitation) and their interactions are essential for natural resource assessment and environmental planning. Changes of attributes involved in natural water systems will influence on many other environmental and natural resource systems such as ecological system and agricultural and fishing activities. In the Greater Toronto Area (GTA), groundwater resource provides water supply for about 15% of the population in urban areas, small towns and rural areas. Groundwater has been proven to be a reliable and economical resource in the GTA. Surface water system provides not only water supply to rivers, ponds and lakes but also for flourishing former land yields and fishing. Precipitation as a natural system not only provides water resources to meet human's need for living but also purifying the environment to keep quality air/water consumption. Understanding of the dynamics of these systems and their interactions in the GTA is crucial for sustainable development and planning. Traditionally the water systems are studied separately on the basis of point observations and with deterministic modeling in a small region with relatively homogenous environments. In the current research, these systems have been studied statistically from data covering a large area and in an integrated manner.

Geological Survey of Canada (GSC) and Ontario Geological Survey had conducted a thorough hydrological and geological study of GTA through the Oak Ridges Moraine National Geoscience Mapping Program (NATMAP) and Hydrogeology Project (1992-1997) (Sharpe et al., 1997). NATMAP Project has provided a foundation both geologically and hydrologically with a comprehensive geoscience database useful for environmental and water resource management in the Oak Ridges Moraine area (Russell et al., 1996). The author's recent studies using the NATMAP database have demonstrated that the spatial aspects of the water systems can play an important role in exploring the interaction of the ground water, surface water and precipitations. The drainage basins and their attributes in terms of geomorphologic, hydrological, geological and ecological properties are evitable factors in modeling of water systems. Application of geographical information systems (GIS) in the ORM database has provided new quantitative and statistical techniques for characterizing the spatial features involved in solving various physical problems. GIS technologies have been applied not only to organize the diverse datasets necessary for the study but also to modeling water distributions from spatial statistical

and stochastic points of view. A high resolution DEM has been substantially used for conducting watershed-based modeling of water systems in the GTA. To name a few examples, surface stream network and drainage basin systems were derived from DEM and the patterns were further quantified and characterized using spatial statistics and non-linear method including multifractal modeling (Cheng et al, 1997, 2001). It was found that patterns of surface stream and drainage basins are associated with lithology types and structural controls in the area. The configuration of the spatial patterns of stream and drainage basins are found related to hydrological variability such as base flow and surface river flow. A watershed-based model process has been developed by Han and Cheng (2000) to estimate the hydraulic properties of glacier deposits in the GTA. The result confirmed that among the various layers of tills and moraine deposits, the moraine deposits, mainly coarser grained unsorted materials (sands, gravels and slit), has higher conductivity in comparison with the Newmarket Tills (dense, stony, and silty sand materials) underneath the moraine deposits. The former may serve as recharging layers and the later as resistance layer to ground water penetration. The streamlines and erosional channels developed in Newmarket Tills may provide potential ground water aquifer. In their MS.c. theses, Lu (2001) employed DEM and river gauging flow data to study the variability of low stream flow and the association with ground water discharge; Zhang (2001) studied the spatial variation of artesian aquifers and their controlling factors from hydrological, geological and geomorphologic points of view. The results confirm that the ground water supplies to river flow may be through flowing wells, spring and seepages etc. (Cheng, 2001). The quantitative results generated from GIS analysis have significantly improved the understanding of the water systems and their associations with geological, geomorphologic and hydrogeological controls in the ORM.

The current paper introduces the general research hypothesis and quantitative models designed for the spatial analysis of water systems and their interactions. The models to be introduced include (1) separation of river flow into components to reflect different sources of surface and ground water supplies; and (2) assessment of spring, flowing wells and seepages to predict influence of ground water supplies to river flows. The methodologies introduced in the paper might be applicable to the similar projects in other areas. The examples demonstrated would show how GIS technologies in conjunction of spatial analysis and fractal modeling can become powerful tools for water system modeling. The further research plan for the area has been also introduced in the paper.

2. Significance of GIS spatial analysis and watershed-based modeling in geological, hydrological and geomorphologic studies

GIS and statistics have been commonly used as tools for handling data and for extracting information to provide decision support. The former provides tools to handle spatial data including for visualization, spatial query and analysis. The later provides techniques for data processing and information extraction. However, traditional statistics packages including SPSS and S-Plus do not consider the spatial aspects of the samples. It generally assumes that the samples are collected randomly and therefore represent populations equally. Most of commercial GIS packages including ArcInfo and ArcView do not have modern statistical capabilities. It is often seen that users either apply statistical techniques to analysis spatial data without knowing the locations of the samples and their representiveness or apply preliminary statistical analysis in GIS. Integration of GIS and statistical techniques has been considered as innovative applications of both GIS and statistics. It may provide unique advantages for effective use of GIS and statistics for the following reasons: firstly, using GIS tools one can generate spatial characteristics to describe the locations of samples such as the relationship of sample locations to topographical, geological and geomorphologic properties which may not be possible without the aid of GIS due to time consuming process or limitation of the ordinary statistical and computing systems. These spatial characteristics can also be incorporated in the calculation of statistics as spatially weighted factor (Cheng, 2000). The samples collected may or may not completely random or independent. In GIS one can define and select samples according various criteria so that selected samples can closely present the properties of the studied population. For example, one can select samples by applying a window defined by specifying an extent, a mask defined by spatial selection or SQL query or weighting layer to give different weights to each sample location so that sample with large weight will represent the population most and sample with small weight will have less representiveness. The spatially weighted samples will be analysis using spatially weighted statistics. In addition to the location properties of samples, some times the samples can be normalized to other variables in order to standardize the samples to reach unbiased results. For example, the flow data for each drainage basin can be normalized with the size of the drainage basin which can remove the influence of the drainage size on the variability of flow data; secondly, equipped with GIS technology, one can easily visualize the locations and the trends of statistical patterns and to compare the statistical results with other spatial information for crosschecking and correlation analysis. This is significant because one can identify outliers and anomalous samples (samples from different populations) and eliminates bad samples from their analysis that can often improve the statistical results. For example, drainage basins derived from DEM in GTA can be

selected as samples for statistical analysis of runoff and river flow. If the values of flow recorded for each drainage basin are plotted against the drainage basin sizes, one may find a high correlation between these two sets of values. The residuals obtained from a linear regression fitted to these two sets of values may behave like random values if just treated as nonspatial values. However, if the drainage basins mapped according to the residuals calculated for each drainage basin, the spatial patterns may show some regular non-random distribution, which may indicate that additional attributes might be needed to explain the variability of the residuals. To view samples in three linked views: map, table and chart, has been found very useful for screening samples for identifying outliers and anomalous samples. Statistical trends can be easily compared with other type of data in the GIS environment, which is often required for further interpretation, and integration of multiple data layers; and thirdly, integrating sophisticated statistics to GIS will greatly improve the GIS capability of solving complex problems involving multi-criteria and multi-factors. For the above reasons a new GeoDAS GIS has been developed at York University in collaboration with Geological Survey of Canada and US Geological Survey (Cheng, 2000). It is fully interactive GIS system with sophisticated statistical and spatial statistical analysis capabilities and variety of new techniques for population unmixing, information extraction and information integration. More information about the system can be found in Cheng (2000). While most of the ordinary statistics including multivariate statistics can be used in conjunction with GIS, some special statistical methods might be particularly useful for dealing with geographical data. For example, due to the weak correlation between spatial features such as between location of flowing wells and the lithology units, semi-quantitative statistics might be more appropriate such as t-test, χ^2 -test and contract (C) from weights of evidence method. These statistics can be used to test the differences between groups of values. Contract (C) calculated in weights of evidence measures the correlation of points occurring on polygon patterns. Since GIS often deals with qualitative variables such as soil types, present and absent of a feature, statistical techniques need to be capable of handling qualitative values. For example logistic regression method is often used to associate occurrence of point events in terms of conditional problem or logit to other variables. Logistic regression. An idea for constructing spatially weighted multivariate has been proposed by Cheng (2000). For example a spatially weighted principal component analysis (PCA) can take samples with a weighting factor as input. For example, for studying alteration for mineral exploration, the samples can be weighted according to the distance from the known alteration zone. A large weight (close to 1) can be given to samples located in the alteration zone and a small weight (close to 0) can be assigned to samples far away from the alteration zone. The spatially weighting factor (proportional to the distance from the alteration zone) will enhance the effect of samples close to the alteration zone on the definition of principal components.

3. Landscape modeling and analysis of water systems interactions in ORM

The study area is chosen as ORM located from the south shore of the Lake Simcoe to the Lake Ontario covering both the north and south slopes of the ORM, from east of Trenton to Niagara Escarpment (Fig. 1) (Sharpe et al., 1997). As a landform made of sand, gravel and silt deposited by receding glaciers, the Oak Ridges Moraine (ORM) is a ridge – 300 meters at its highest point – that stretches 160 km from the Niagara Escarpment in the west to the headwaters of the Trent River in the east (Kanter, 1990). It is the regional surface water division between water flowing south to Lake Ontario and water flowing north to Lake Scugog, Lake Simcoe, Rice Lake and Georgian Bay. As a huge water recharge, discharge and storage area, it is essential for maintaining base flow in the stream systems and water levels in kettle lakes in the GTA. It serves 15% ground water resource for the drinking water for the area. In recent years, there is increasing demand for the moraine's surface water and groundwater resources for residential, commercial, industrial and recreational uses (Storm, 1997).

Sharpe et al. (1997) has established a geological model consisting of six principal stratigraphic elements for the area, which has served as the geological hypothesis for characterizing spatial variability of river flow, ground water aquifers and ground/surface water system interactions etc. Among these six lithology elements, the ORM is an extensive stratified glaciofluvial-glaciolacustrine deposits 150km long, 5 to 15km wide and thickness up to 150m. It forms a prominent ridge of sand and gravel running from near Rice Lake to the Niagara Escarpment (Fig. 1). The lower contact of the ORM is an irregular channeled surface of Newmarket Till. The channels may be confined within, or have eroded through, the Newmarket Till into the lower drift below. It is generally recognized that the ORM is the main source of recharge in the region. Studies have also indicated that recharge may also take place through the till units adjacent the moraine. The channels developed in the Newmarket Tills contain mainly sandy sediments related to the ORM complex and some channels contain thick gravels. These channels may be hydrologically significant as high yield aquifers (Sharpe et al., 1997). To test the influence of ORM on the ground and surface water interactions, several models have been implemented as will be introduced in the following sections. One model was to characterize the spatial distribution of ground water aquifers especially the location of artisan aquifers through the study of locations of flowing wells, spring and seepages. The

second model is to analysis river flow data to associate low river flow to potential ground water supplies. The third model is to analyze the association of precipitation and runoff in the area. To understand the associations and balances of the water systems (precipitation, surface and ground water) interactions is the main objective of the study.

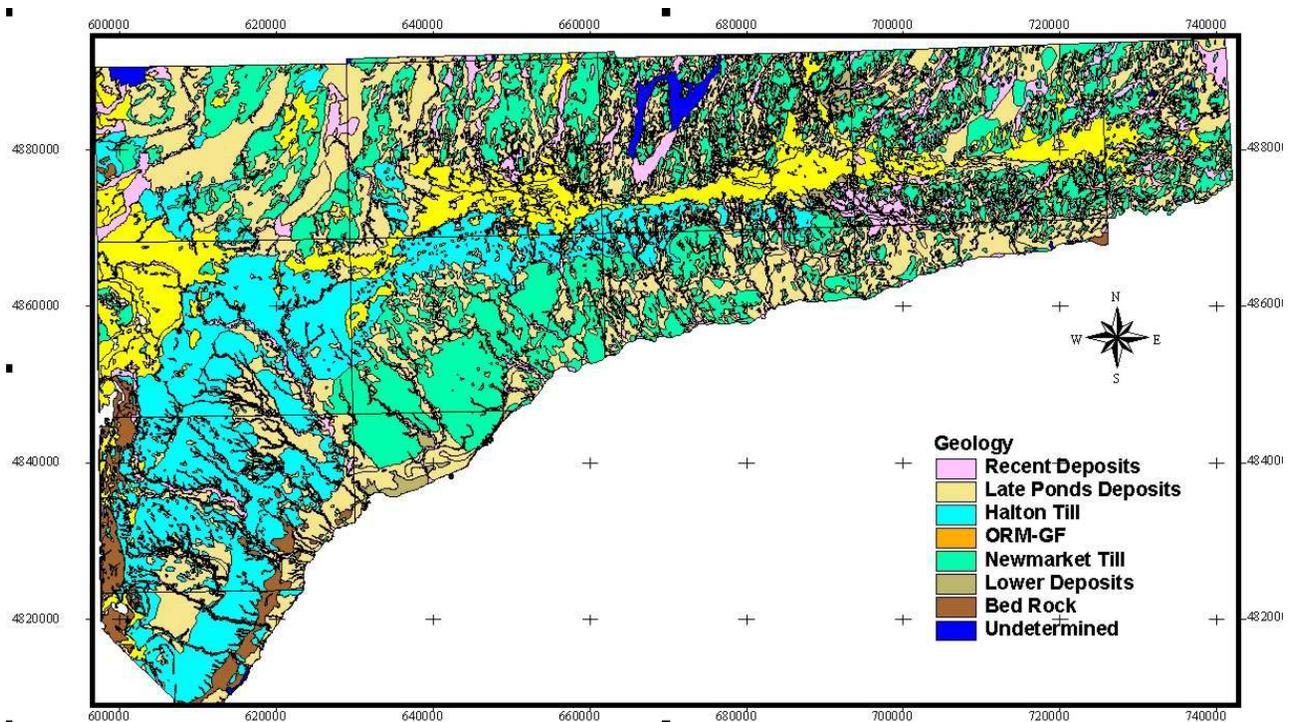


Figure 1. Surficial geology of the ORM (Sharpe et al., 1997)

3.1. Ground and surface water distributions and their interactions

It is generally recognized that groundwater discharge is one of the main contributors to the low flow of streams in the Oak Ridges Moraine Area. Groundwater discharge to streams may be through spring, flowing wells, and seepages where the water level can reach the surface. A number of big spring sites have been well documented, the economically less significant springs and most areas with seepages, however, still remain unknown. Artesian wells are wells with water levels above the surface due to hydrostatic pressure. From about 57000 water wells from the newly revised MOEE dataset by Geological Survey of Canada, 353 were selected with water levels above the surface. The spatial distributions of these wells are shown in Fig. 2, superimposed on DEM. It can be intuitively seen from the locations of wells in Fig. 2 that most of the wells are located in those areas with negative relieves and nearby some kinds of steep slope zones, which may cause hydrostatic pressure due to significant gravity difference. Therefore, spatial correlation between the locations of wells and the distances from the high slope zones was tested. Neighbourhood statistics applied to all the wells have suggested that these artesian wells can reasonably represent the water wells in terms of seasons, years and depths of wells as well as density of well distribution (Zhang, 2001). Therefore, these artesian wells can be chosen as samples representing the areas with water table above the surface. The locations of the artesian wells show an irregular and clustered distribution. The question to be asked is whether the locations of these artesian wells have anything to do with geological, topographical and hydrological features? In order to analysis the spatial distribution of flowing wells and their spatial association with other spatial features, various features have been extracted and defined with the aid of GIS. For example, the distance from ORM, the slope and the drift thickness etc. were constructed using ArcView GIS. To calculate the spatial correction between point features and line or polygon features, the weights of evidence method (Bonham-Carter, 1994) was applied. The method can be used to find optimum cut-off values to construct binary evidence. It has been demonstrated that the locations of artesian wells in the ORM area are correlated with the distances from ORM, thick drift layer and steep slope zones within the

arranges of 500 – 5000m to ORM, 500-4000m to thick drift layer and 1500-2500m to the steep slope zones, respectively (Cheng, 2001). The combination of distances from ORM and from steep slope zones yields higher correlation and the cells

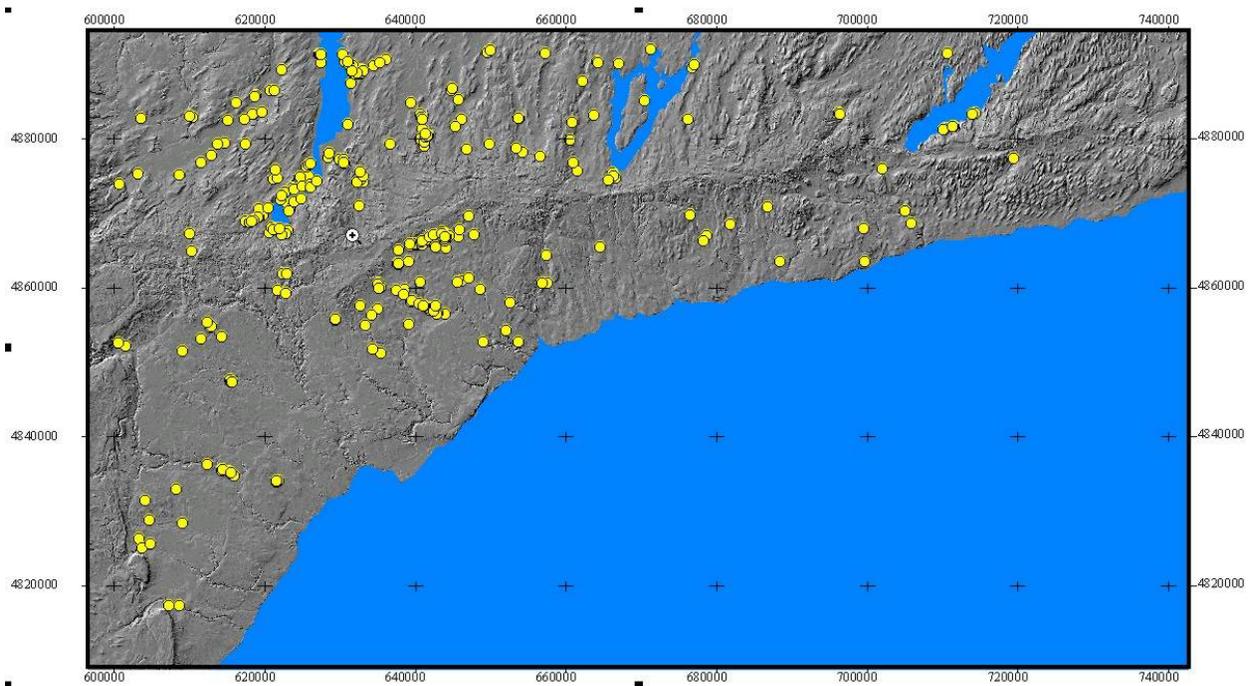


Figure 2. Artesian wells in the Oak Ridges Moraine area extracted from MOEE dataset (Cheng, 2001). Background map is the shaded-relief DEM with 30-meter resolution (Kenny, 1997).

with this combination may have posterior probabilities of having at least one flowing well three times higher than the prior probability of the randomly selected cells from the study area (see Fig. 3). The posterior probability map can be further integrated to other layers of data to study the interactions of ground and surface water systems. More detailed study by Zhang (2001) in his MS.c. thesis was devoted to check into the spatial association of flowing wells with several other evidence layers including layers created from water well data such as elevation of sand and gravel layers recorded in water wells. Due to the interdependency of the multiple evidential layers Zhang used multiple logistic regression model with 9 binary evidential layers to predict the potential areas where flowing wells may occur (see Fig. 4). The high potential areas with potentiometric surface of the upper artesian aquifer might be above the land surface are mainly located in the Laurentian Channel area, south of the boundary of Oak Ridges Moraine, and creek valleys. The study confirmed that regional geological, topographical and hydrogeological features are important influence factors on the spatial distribution of groundwater in this area. It has been demonstrated that weights of evidence and logistic regression models can be used to characterize the aquifers and their relationships with other geological and topographical features, and to make predictive map for regional artesian aquifers from the water well data.

3.2. River flow analysis

Maintaining river flow is important not only for water supplies for human livings but also for maintenance of environmental sustainable development in the GTA area. Water supplies for river flow can be made through ground water discharge or surface run off. The ground water discharge provides a long-term sustainable component maintaining the low flow (base flow) that is relative stable flow independent of seasonal precipitation. The surface runoff and overland flow usually correspond to precipitation and influenced by the topographical features such as soil types, vegetation cover, and stream network and drainage systems. Studies based on the stream discharge records obtained from about 70 gauging stations monitored by the Water Survey of Canada more than 30 years, baseflow, the part of stream discharge from ground water seeping into the stream, is lower in western watersheds and higher in eastern watersheds. Differences in the baseflow per unit watersheds area suggest spatial differences in groundwater flow across topographic divides (Hinton, 1996). Significant spatial differences in baseflow are also noted within individual basins (Sharpe et al., 1998). In order to a

conduct through spatial analysis of river flow in the ORM area, a more updated river flow records from the HYDAT database (Environment Canada, 1999) were extracted and 98 gauging stations were selected from the database (see Fig. 6).

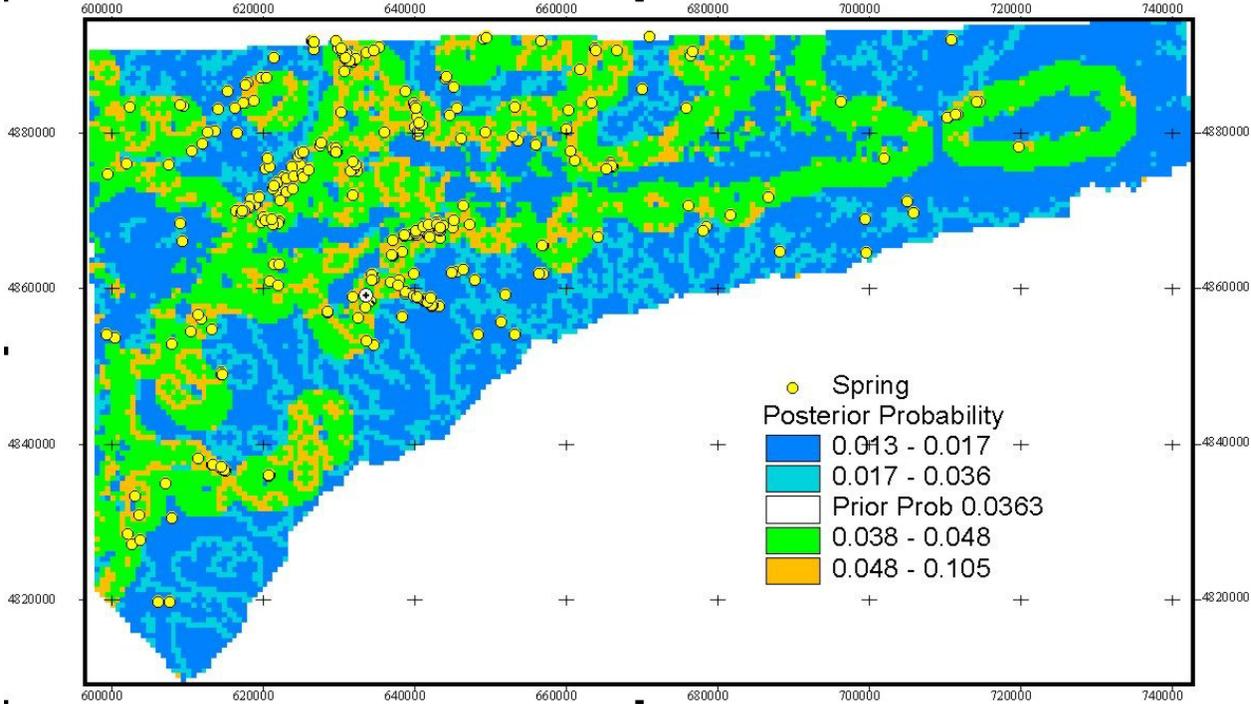


Figure 3. Posterior probability map calculated by Arc-WofE on the basis of the buffers around ORM and steep slope zones (Cheng, 2001).

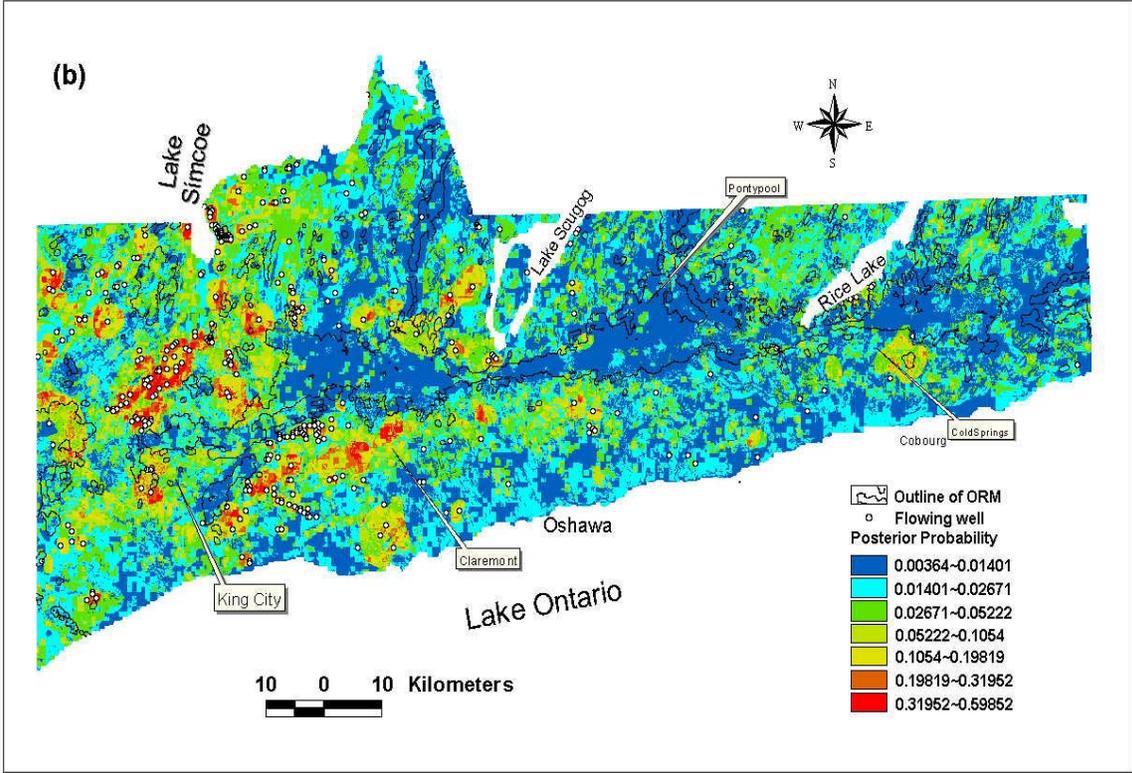


Figure 4. Posterior probability map calculated by logistic regression with 9 binary evidence layers (Zhang, 2001).

To decompose the river flow into separated components to reflect baseflow and surface flow, an integrated statistics and spatial analysis was developed. The general idea was proposed and presented by Cheng (2001) illustrated as a flow chart in Fig. 5. The processes consist of two main steps: the first step involves frequency analysis and the second step deals with spatial analysis. In the first step, river flow is separated into low flow and residual flow on the basis of flow frequency. The low flow is the basic component reflecting the “baseflow” variability. Lu has implemented the model in her MS.c. thesis (Lu, 2001). The residual flow is the component closely corresponding to the seasonal precipitation changes. Lu (2001) calculated the low flow using two methods one of which is to calculate the average of 30-days minimum flow values for up to many years. The low flow calculated in such may still contain flow component due to surface run off, which can be confirmed by plotting the low flow against drainage basins and their attributes such as size of drainage basins, perimeter of drainage basins and total length of stream segments in drainage basins. If we assume that ground water discharge to the rivers are limited to the small areas where aquifers are exposed on or near surface, then these types of ground water discharge will be relative independent of drainage basins. Therefore, in the second step of the process, the low flow was plotted against drainage area size related attributes. A multivariate regression was then fitted to the low flow values and the drainage area size related

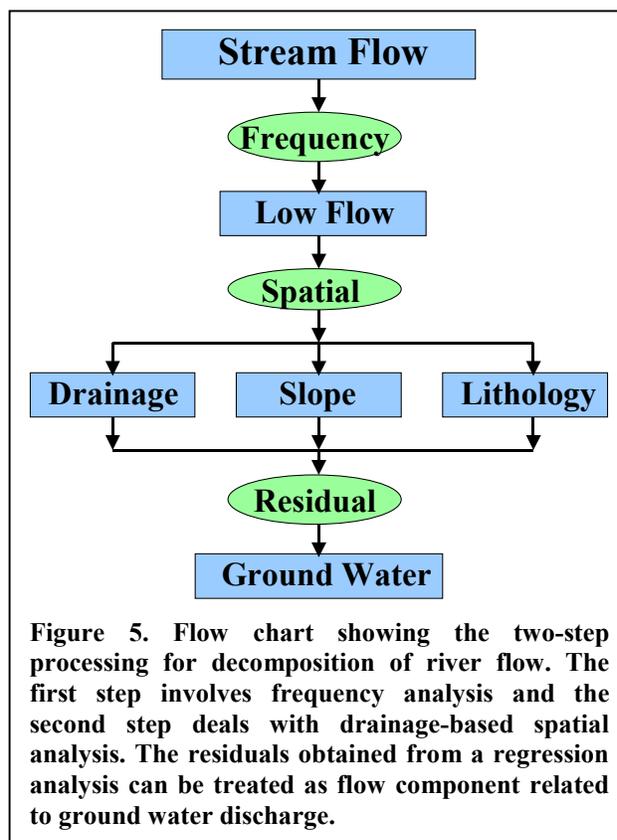


Figure 5. Flow chart showing the two-step processing for decomposition of river flow. The first step involves frequency analysis and the second step deals with drainage-based spatial analysis. The residuals obtained from a regression analysis can be treated as flow component related to ground water discharge.

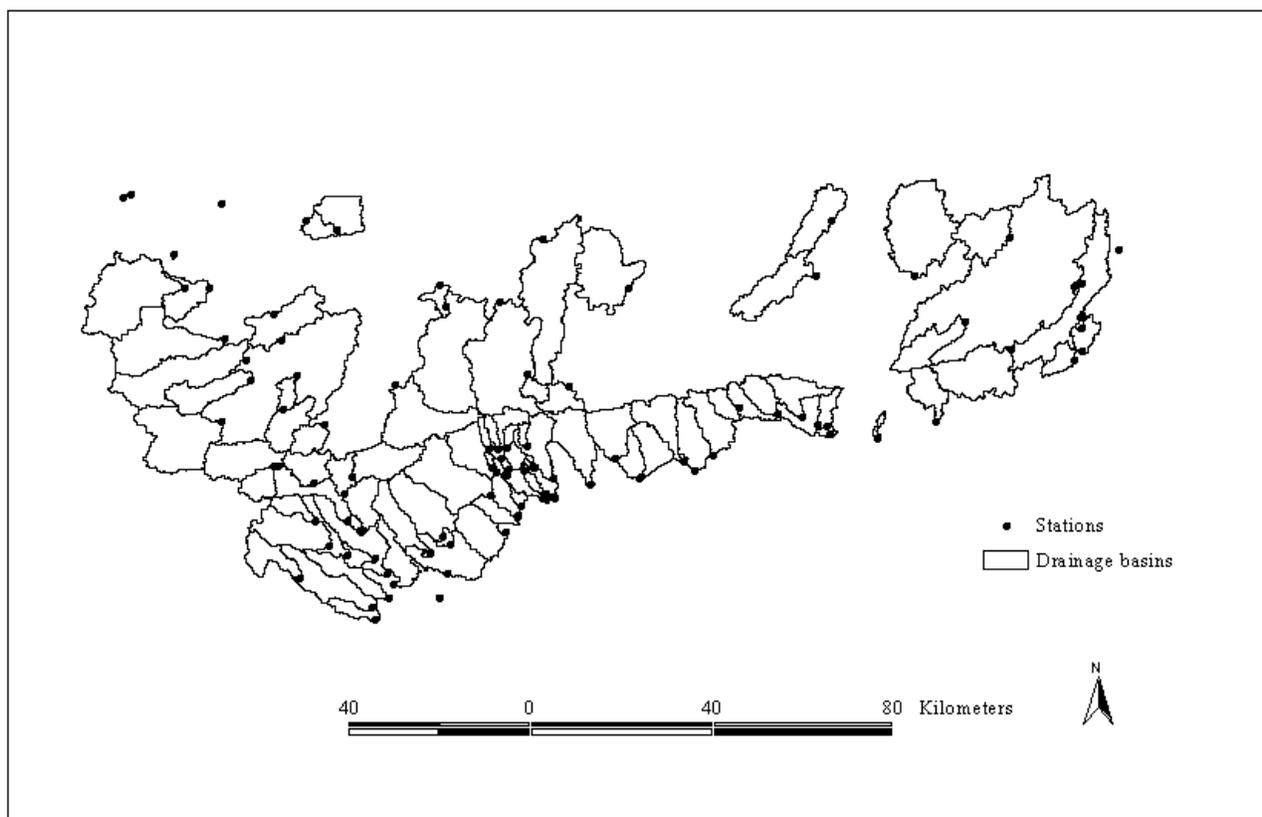


Figure 6. River gauging stations and drainage basins derived from DEM (from Lu’s MS.c. thesis, 2001)

attributes. Significant correlation has been demonstrated between the low flow and the drainage-related attributes.

The residual values of the regression, independent of all the drainage-related attributes, can be treated as the low flow component, mainly representing the component due to ground water supply (see Fig. 7). The result of Lu's work (2001) has demonstrated that a significant component of low flow in the area might be due to ground water discharge. More detailed implementation and discussion about spatial variability and association with geological, hydrological and topographical features can be found in Lu (2001).

3.3. Precipitation and runoff

The previous discussions have concluded that the ground water and surface water system interactions is significant and the water supplies from surface and ground to river flow are significant in maintaining river

systems in the area. In order to completely understand the balance of precipitation, ground water and surface water systems, the connection and regularity between precipitation and runoff has to be further examined. In an ongoing project, weather network data will be used to support the study. Since river gauging stations and weather network stations are not from the same sites, these data have to be associated in the watershed context. Multiple year records will be used for the statistical study. The focus of the study will be given on demonstrating the correlation of precipitation and seasonal variable river

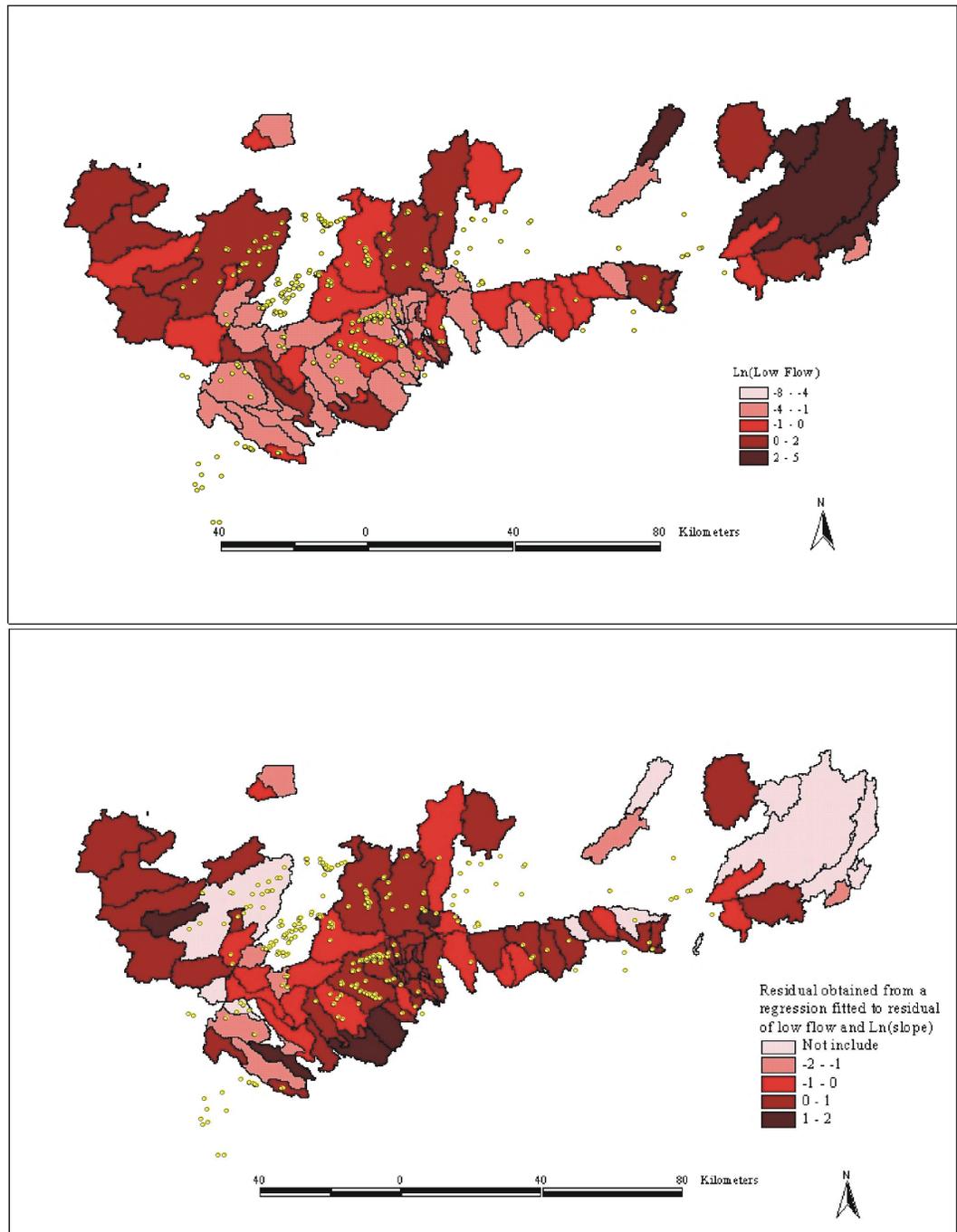


Figure 7. Drainage basins colored according to river flow values: Top map – log-transformed flow values and bottom map- residuals obtained from regression. The residuals correspond to the decomposed low flow values representing ground water discharges. Yellow dots are flowing wells (from Lu's M.S.c. Thesis, 2001).

flow. This will assist in further separation of short-term and long-term precipitation-controlled river flows in addition to the recognition of ground water discharge-related low flow.

4. Conclusions and discussions

Various spatial analysis models proposed and applied to the diverse datasets from ORM have demonstrated that spatial aspects of the water systems are essential for understanding the interactions between ground water and surface water systems on the basis of point observations and measurements made at river gauging stations, water wells and weather network stations. Integration of GIS and statistics can provide powerful tools for solving complex problems such as separation of baseflow and surface flow which might not be possible without taking into account the spatial associations of flow data and other geological, hydrological and topographic features. The quantitative results have demonstrated that ORM, as unique glacier deposits, plays an important role in maintaining the water distribution and balance in the area. ORM provides significant aquifers for the GTA and the contact between ORM and Newmarket Tills has good potential to become significant ground aquifer for the area. The environmental sensitivity of water systems of the area should be carefully considered when urban development to be planned in the ORM.

5. Acknowledgements

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