EXPLORING THE DYNAMICS OF GROUNDWATER AND CLIMATE INTERACTION

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ABSTRACT
Base flow index and recession are used as indicators of the dynamics of groundwater and climate interaction within south-central and southwestern Ontario. Base flow index is a measure of the rate of groundwater discharge relative to stream flow and base flow recession is a measure of the timing of discharge in response to recharge. Estimates of the indicators are determined by sub-watershed and compared to physiographic factors. Terrain and characteristics of the overburden and bedrock are leading constraints on the spatial variation of the indicators and result in differing sensitivities to climate variability and change. This information is useful in assessing the capacity of the groundwater resources of the region to simultaneously function as a water supply and maintain in-stream conditions subject to varying water availability.

RÉSUMÉ
L'indice et la décrue du débit de base sont utilisés comme indicateurs de la dynamique des eaux souterraines et l'interaction de climat dans Ontario sud-central et du sud-ouest. L'indice du débit de base est une mesure de la cadence d'écoulement fluvial relatif de décharge d'eaux souterraines et la décrue du débit de base est une mesure de la synchronisation du débit en réponse à la réalimentation. Des évaluations des indicateurs sont déterminées par sub-bassin hydrographiques et comparées aux facteurs physiographiques. Le terrain et les caractéristiques des terrains de recouvrement et de la roche en place sont de principales contraintes sur la variation spatiale des indicateurs et le résultat dans des sensibilités différentes à la variabilité et au changement climatiques. Cette information est utile en évaluant la capacité des ressources d'eaux souterraines de la région de fonctionner simultanément comme approvisionnement en eau et de mettre à jour des conditions dans cours d'eau sujet à la disponibilité variable de l'eau.

1. INTRODUCTION

Public, media, and political interest in groundwater issues within Ontario have increased dramatically during recent years. The reasons for this trend include the reduced water availability that was associated with drought-like conditions that persisted from mid 1997 through early 2000; increased awareness of existing commercial uses of groundwater and proposed bulk water exports from the Great Lakes; urban and rural development, particularly the concentration of some agricultural practices and proposed changes to land use on the Oak Ridges Moraine; and the tragic results of the contamination of the water supply of Walkerton by *E. coli* bacteria.

Water scientists and engineers, managers, and policy makers variously acknowledge that groundwater has two distinct functions in Ontario, in many other regions of Canada, and internationally. The first of these functions is societal; for example, it is estimated that 30 percent of the total population of Ontario, and 90 percent of the population in rural areas of the province, are dependent on groundwater for their water supply. Much of the supply in rural areas is drawn from wells that were constructed to provide a reliable supply subject to prevailing climate and water use. The recent drought-like conditions led to wide-spread reports of reduced groundwater levels. In some cases, these lower levels resulted in the partial impairment of water supplies; in other cases, supplies were lost entirely. Thus, there is ample evidence that groundwater conditions respond to even short-term reductions in water availability and that this relation readily translates to tangible societal implications. If these variations are an approximation of longer-term climate change, then similar implications are probable. The discharge of groundwater to wetlands, lakes, and rivers is often critical to aquatic habitat. For example, certain aquatic species survive and reproduce only in areas of elevated groundwater discharge. In-stream water quantity and quality parameters such as flow, level, temperature, and dissolved oxygen are generally favorable in these areas, and were also diminished during the recent drought-like conditions. Thus, groundwater has a ecological function that is climate dependent and simultaneous to its societal function as a water supply.

This study that is reported in this paper is an extension of earlier research that was specific to the Grand River watershed in west-central Ontario (e.g., Moin et al. 1998, Piggott et. al 2000). The purpose of the current study is to develop an improved understanding of the dynamics of groundwater and climate interaction - the manner in which groundwater conditions respond spatially and temporally to climate - within a larger and more diverse study area. This understanding can then be used to better assess the sensitivity of groundwater resources to climate variability and change. Because groundwater discharge as base flow can be estimated from stream flow, and because stream flow data is widely available for southern Ontario, determining indicators of base flow is a practical approach to exploring the dynamics of groundwater and climate interaction. This approach, and an analysis of the relation of the indicators to physiographic factors, are the focus of this paper.

2. DESCRIPTION OF THE STUDY AREA

The coverage of the study is illustrated in Figure 1. The study area extends from Lake St. Clair and the Detroit and St. Clair Rivers in the west to the Regional Municipality of Durham and Simcoe County in the east and from Lake Erie, the Niagara River, and Lake Ontario in the south to Lake Huron and Georgian Bay in the north. The dimensions of the area are approximately 380 km from west to east and 400 km from south to north; the total land area is roughly 53,000 km^2. Census statistics indicate that the population of the area is in excess of 8.1 million and that the rate of population growth is roughly 2 percent per year. Much of this population, and growth, is within urban municipalities that are located along Lake Ontario from Hamilton to Oshawa and along the Highways 400 and 401 corridors.

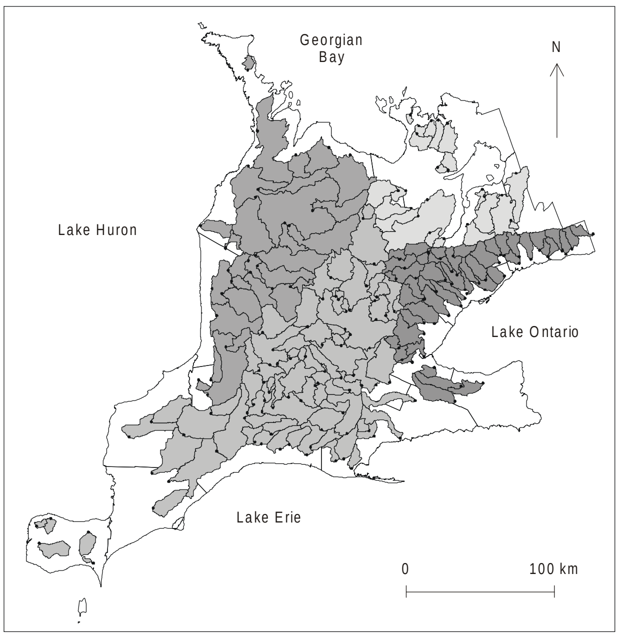


Figure 1. Location of the study area.

The shaded area in Figure 1 indicates the network of 174 sub-watersheds that is used in this study. Each of these sub-watersheds is tributary to a Water Survey of Canada stream flow gauge. Parameters such as stream flow, lake and river levels, and sediment transport are measured at these gauge locations on a daily basis and are published annually on CD ROM. The shading applied to the network indicates drainage to Georgian Bay, Lake Huron, Lake Erie, and Lake Ontario. Portions of the study area are not covered by the network of sub-watersheds, either because it is not feasible to gauge stream flow in these regions or because only limited data is available for the corresponding gauges. While groundwater conditions within these regions cannot be determined directly, it is possible to estimate conditions using relations to physiography developed in the gauged regions.

3. ESTIMATION OF BASE FLOW

Daily stream flow data for each of the stream gauges and the period of 1970 to 1998 were extracted from a recent version of the HYDAT CD ROM (Environment Canada 1999) and formatted as time series. Base flow was then calculated from the time series using the turning points method implemented within a relational database setting. A comparison of this and other methods of base flow separation is presented by Natham and McMahon (1990). Next, the output sequences of turning points were interpolated to match the input time series of stream flow.

Figure 2 illustrates the results of these calculations for the sub-watershed that is tributary to stream flow gauge 02HC022, the Rouge River near Markham, during 1973. The base flow indicators for this sub-watershed most closely approximate the median values of the indicators calculated for the network of sub-watersheds and the base flow calculated for 1973 most closely approximates the median value of the annual base flows for the sub-watershed. The upper portion of the figure illustrates the input daily time series of total flow and output series of base flow where total flow is equal to direct surface runoff plus base flow. The abscissa indicates the sequencing of the series relative to January 1, 1900. The lower portion of the plot illustrates the corresponding monthly time series of runoff and base flow where the flows are reported as an equivalent depth relative to the area of the sub-watershed. In this case, the abscissa indicates the sequencing of the series relative to January, 1970. Similar monthly time series for up to 348 months (January, 1970 through December, 1998) were calculated for each of the sub-watersheds. In cases where other stream flow gauges are located upstream of a gauge, the flows for the downstream gauge are differentiated such that the values reflect only the contribution of the sub-watershed that is immediately tributary to the gauge.

4. DEFINITION OF BASE FLOW INDICATORS

Base flow index, α, is defined as the ratio of the long-term averages of base flow and total stream flow and is a dimensionless parameter within the range $0 \le \alpha \le 1$. Small values of base flow index indicate a minimal contribution of groundwater discharge to stream flow while large values indicate a significant contribution. Base flow index is, however, a measure of only the average rate of groundwater discharge. The timing of discharge in response to groundwater recharge is also an important indicator. For example, where the drainage of groundwater is rapid, discharge and base flow may not be adequately persistent to maintain in-stream conditions during the typical annual low flow period of July through September, and particularly during sustained periods of reduced water availability such as the drought-like conditions of mid 1997 through early 2000.

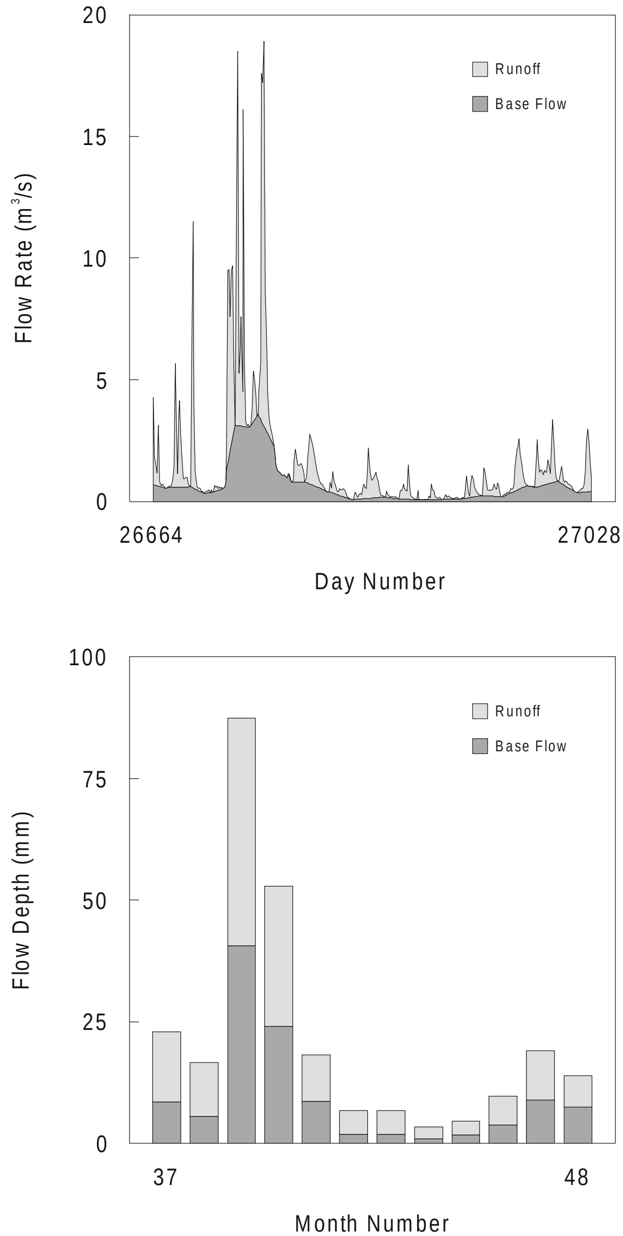


Figure 2. Typical time series of runoff and base flow.

Numerous mathematical relations are used to describe the variation of groundwater discharge following an isolated and short-term recharge event. A relatively simple approximation (e.g., Linsley et al. 1982) is

$$Q = Q_o K^t \quad [1]$$

where Q is the discharge at time t, which is typically measured in days, Q_o is an initial discharge, and K is a recession constant. If a monthly time series of base flow is defined, and if continuous and uniform recharge during the first month of this series (i = 0) is assumed, then the discharge during any other month (i > 0) is given by

$$V_i = -\frac{R}{\ln K}(1-K^{\Delta t})(K^{(i-1)\Delta t} - K^{i\Delta t}) \quad [2]$$

where R is the recharge rate of the event and Δt is the average duration of each month of the series. The discharge during the subsequent month is given by

$$V_{i+1} = -\frac{R}{\ln K}(1-K^{\Delta t})(K^{i\Delta t} - K^{(i+1)\Delta t}) \quad [3]$$

and the ratio of the two rates of discharge is

$$\frac{V_{i+1}}{V_i} = K^{\Delta t} \quad [4]$$

which can also be expressed as

$$V_{i+1} = \beta V_i \quad [5]$$

where β is the indicator of base flow recession that is used in this study. Groundwater discharge in response to recharge is both infinite and decaying and therefore base flow recession is a dimensionless parameter within the range $0 \leq \beta \leq 1$. Increasing values of base flow recession indicate more persistent discharge and base flow and are characteristic of increasingly favorable groundwater discharge conditions.

The discharge that occurs during the first month of the series (i = 0) is

$$V_i = -\frac{R}{\ln K}(K^{\Delta t} - \Delta t \ln K - 1) \quad [6]$$

and the ratio of this rate and the rate for the following month (i = 1) is

$$\frac{V_{i+1}}{V_i} = \frac{(1-K^{\Delta t})^2}{K^{\Delta t} - \Delta t \ln K - 1} \quad [7]$$

which, in terms of base flow recession, is

$$V_{i+1} = \frac{(1-\beta)^2}{\beta - \ln\beta - 1} V_i \ . \qquad [8]$$

These expressions define a response function, f_i, that predicts monthly base flows in terms of base flow recession and a monthly scale recharge rate. This function is most easily constructed by assuming $f_i = 1$ for the first month of the series and then calculating the value for the second month using Equation 8 and the value for the third and subsequent months using Equation 5. Conservation of mass requires that the sum of the elements of the response function is unity and is achieved by normalizing the elements of the function.

Figure 3 illustrates the fraction of a recharge event that is discharged during months i = 0 through 24 where only fractions greater than one percent of the event are plotted. Three sets of results are shown where these sets correspond to the minimum, median, and maximum values of base flow recession calculated for the network of sub-watersheds. In the case of the minimum value, significant discharge (i.e., greater than one percent of the recharge event) occurs only during the event and the first month following the event. Significant discharge occurs for three months following the event in the case of the median value, and for 23 months in the case of the maximum value.

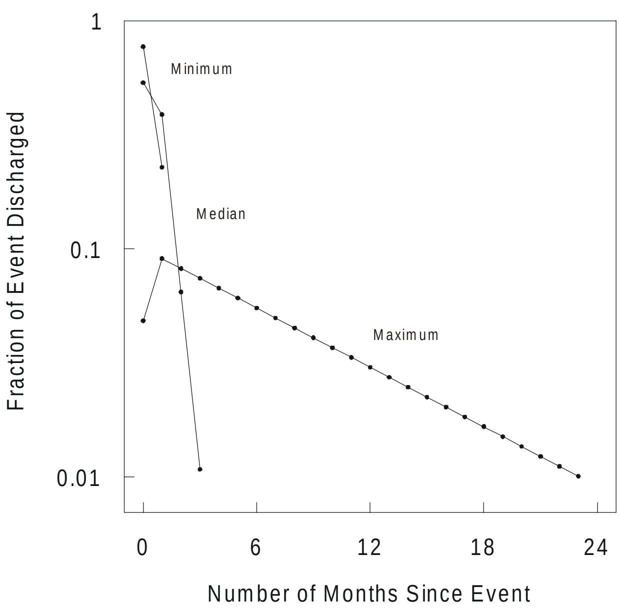


Figure 3. Response functions for selected values of base flow recession.

Figure 4 is a plot of the calculated monthly time series of base flow, averaged for each month of the year and normalized with respect to the sum of these averages. Results are shown for the sub-watersheds that most closely match the minimum (stream gauge 02HA020 located on Twenty Mile Creek above Smithville), median (02HB004 located on East Oakville Creek near Omagh), and maximum (02HB018 located of the Credit River at Boston Mills) values of base flow recession. The contrast between the flows during March and April and during July through September decreases as base flow recession increases because discharge becomes increasingly persistent, with less discharge occurring during March and April and more discharge occurring during July through September. Clearly, if all other factors are equal, then in-stream conditions will be more favourable in areas characterizes by larger values of base flow recession than in areas characterized by smaller values.

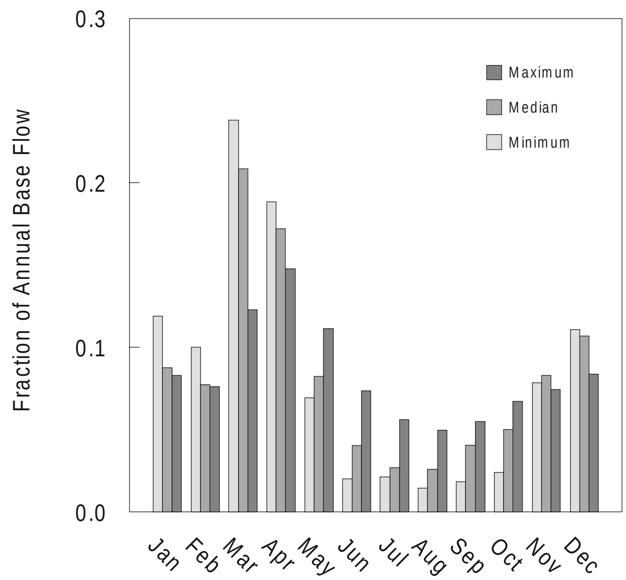


Figure 4. Annual distributions of base flow for selected values of base flow recession.

5. CALCULATION OF BASE FLOW INDICATORS

Surface runoff responses for watersheds in the study area are typically a few days in duration. Thus, the runoff calculated for a given sub-watershed and month is an indicator of the precipitation that occurred during that month and is in excess of abstractions such as evapo-transpiration and changing soil moisture. If the partitioning of this excess precipitation into runoff and groundwater recharge is constant, then a monthly time series of groundwater recharge events can be approximated using

$$r_i = \frac{\alpha}{1-\alpha} s_i \qquad [9]$$

where r_i and s_i are the depths of recharge and runoff. The response function predicts a time series of base flow following an isolated recharge event. Predictions for a series of events can then be superimposed to approximate base flow as a function of the history of events. The resulting relation is a convolution (e.g., Wylie and Barrett 1982) and has the form

$$b_i = \frac{\alpha}{1-\alpha}\sum_{j=0}^{n_f} f_j s_{i-j} \qquad [10]$$

where n_f is the number of elements forming the response function. The initial portion of the estimated time series of base flow is not accurate due to the limited previous history of recharge. The duration of this portion is governed by the duration of the response function and the convolution approximation typically stabilizes within a few months (see Figure 3).

In this application, runoff and base flow are both known and therefore it is possible to determine the values of base flow index and recession that correspond to the estimated time series of base flow that most closely matches the known series. These optimal values correspond to the minimum value of the error function

$$E(\alpha,\beta) = \sum_{i=1}^{n_b} | b_i - b_i^* |^m \qquad [11]$$

where b_i and b_i* indicate the known and estimated series of base flow and m is an arbitrary exponent. The error function is non-linear with respect to base flow index and recession and therefore the values of the parameters must be determined using constrained, multivariate, non-linear minimization (e.g., Press et al. 1992). In this case, estimates of the base flow index and recession were constrained within the ranges $0.01 \leq \alpha \leq 0.99$ and $0.01 \leq \beta \leq 0.95$ and the exponent m = 1 was used.

The correlation of the input and output series of base flow for each sub-watershed can be readily calculated and provide an indication of the accuracy of the convolution approximation. The values of the coefficient of correlation, ρ, are mapped by sub-watershed in Figure 5. The results are classified into three groups; namely, sub-watersheds where negative correlation was achieved ($\rho < 0$), where relatively weak positive correlation was achieved ($0 \leq \rho < 0.5$), and where relatively significant correlation was achieved ($\rho \geq 0.5$). Negative and weak correlation indicate that the convolution approximation performs poorly. This condition occurs, for example, in sub-watersheds where flow regulation is used to control flooding and low flow conditions. The approximation also performs poorly in several of the sub-watersheds that are located north of Lake Ontario in the vicinity of the Oak Ridges Moraine. This may be the result of the complex, three-dimensional groundwater flow regimes that exist within the Moraine.

Base flow index and recession were successfully calculated for 167 of the network of 174 sub-watersheds. Both indicators reflect anthropogenic factors such as flow regulation and waste water discharge and therefore 142 of the 167 values were retained for sub-watersheds where these factors are limited; 98 of these values were then selected for sub-watersheds where significant positive correlation of the series of base flow was achieved. A second application of the deconvolution process was performed using a modified version of the error function (m = 2) in order to identify sub-watersheds where the deconvolution is poorly posed and the estimates of base flow index and recession are not reliable. The resulting, final selection of 82 of the 98 values of base flow index and recession was made following the second application of deconvolution.

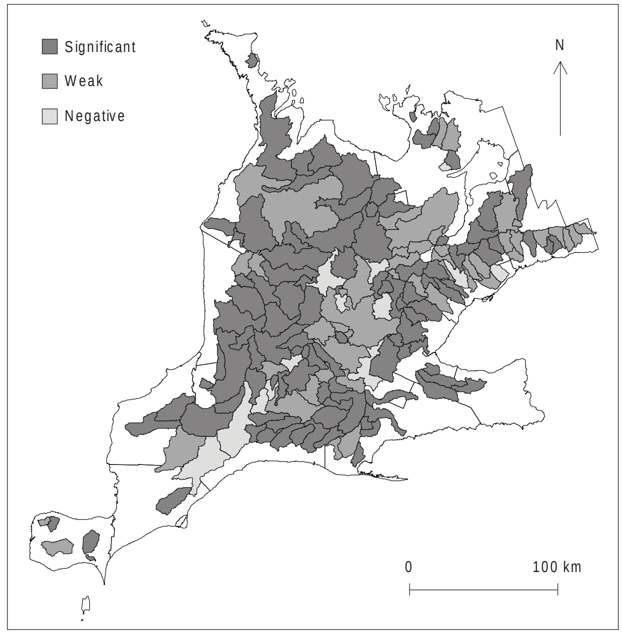


Figure 5. Spatial variation of the correlation of the known and estimated time series of base flow.

Histograms of the 82 values of base flow index and recession are shown in Figure 6. Both histograms are skewed toward the upper ends of the ranges of values. The plots that are inset into the histograms compare the calculated cumulative distribution functions of the values to cumulative distribution functions of log-normal distributions fit to the values. Both calculated distributions are well represented by the log-normal distributions, confirming the skewed appearance of the histograms. This result indicates that base flow index and recession are most populous toward the lower ends of the ranges of values; however, this characteristic is most pronounced for base flow recession. Thus, there are a relatively few sub-watersheds where base flow index and recession are high and where groundwater conditions are particularly favourable. If these regions can be confirmed using supporting data such as observations of the quality of aquatic habitat and species distributions, then it may be possible to verify the use of base flow index and recession to classify the ecological potential of the tributary wetlands, lakes, and rivers.

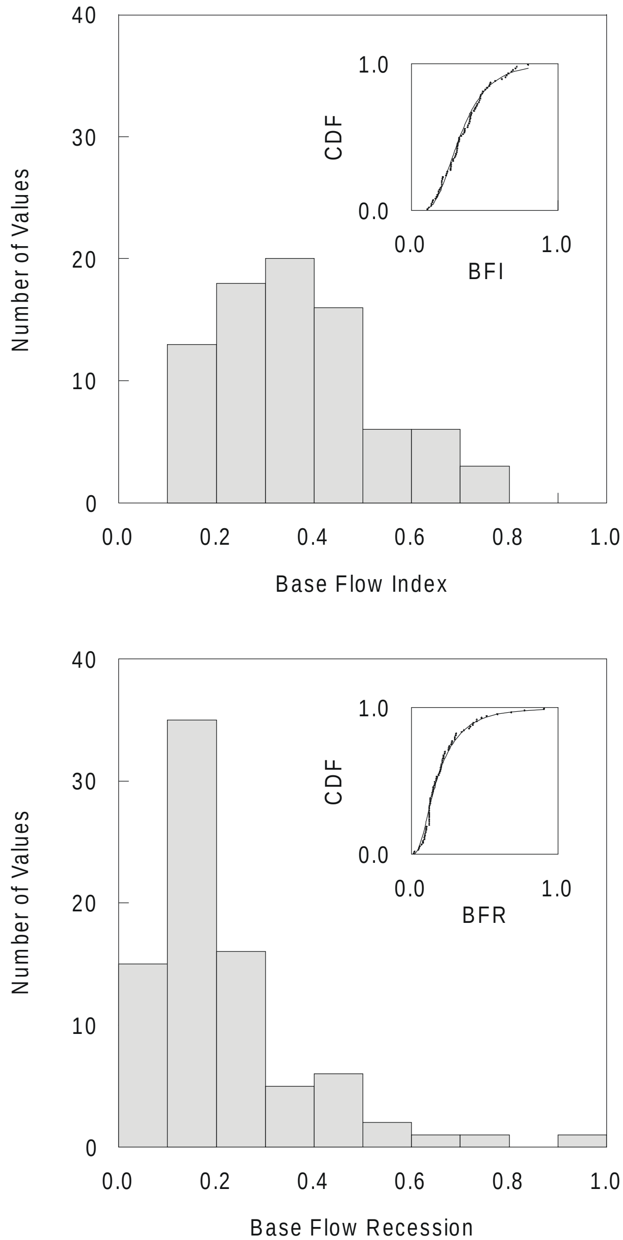


Figure 6. Distributions of base flow index (top) and recession (bottom).

The selected values of base flow index and recession are mapped in Figure 7. Several patterns are apparent in the results. For example, the values of both parameters are relatively high in the northwestern portion of the Regional Municipality of Haldimand-Norfolk, north of Long Point. This region is characterized by extensive deposits of glaciolacustrine sand and gravel. Conversely, the values of both parameters are relatively low in the sub-watersheds of Twenty Mile Creek along the southern shore of Lake Ontario where deposits of glaciolacustrine silt and clay are predominant. This suggests that physiographic factors summarized by Quaternary geology are important constraints on groundwater conditions.

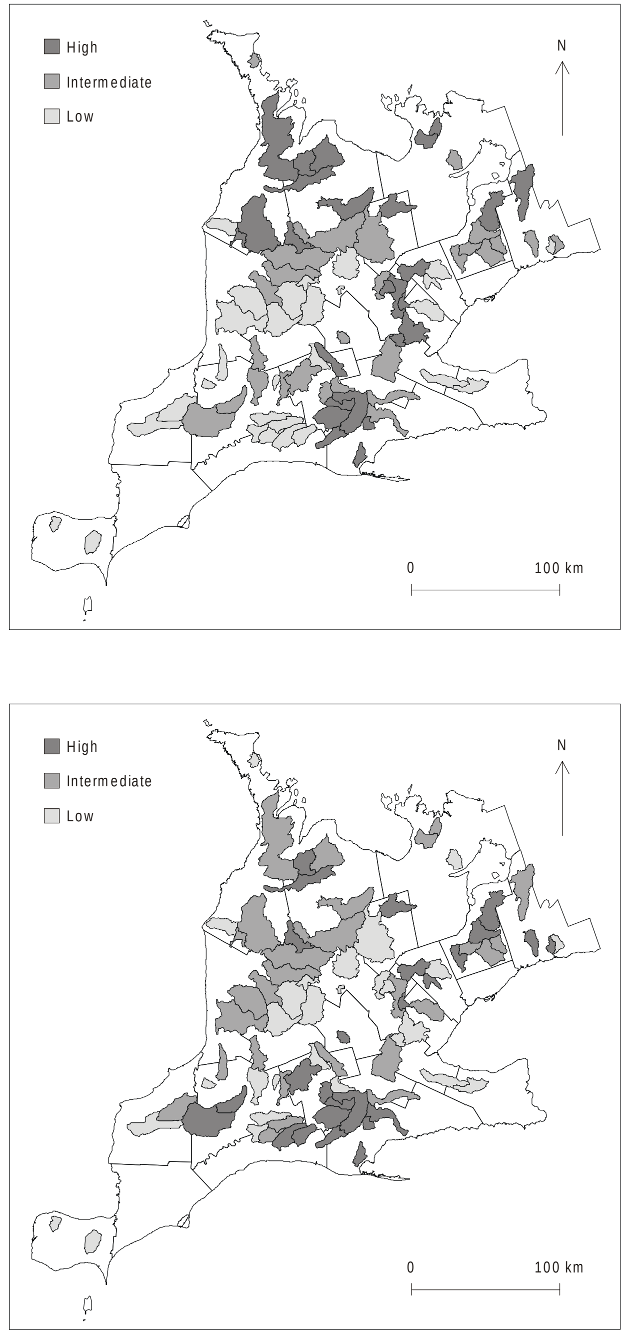
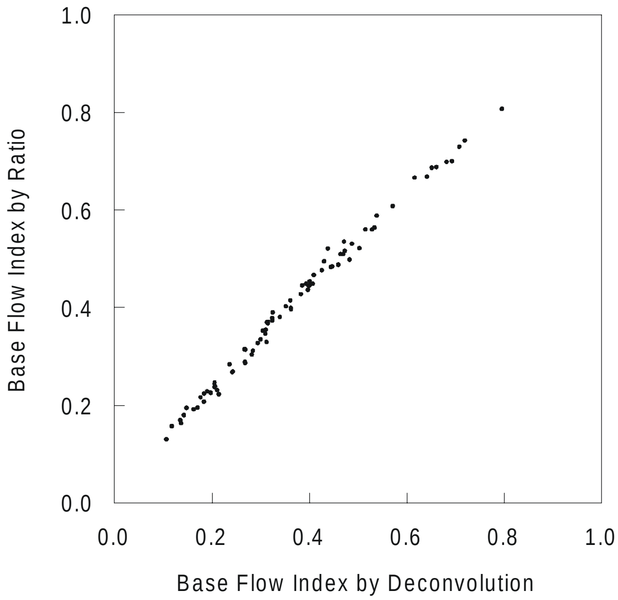


Figure 7. Spatial variations of base flow index (top) and recession (bottom).

It is possible to directly determine analogues to the values of base flow index and recession determined by deconvolution. An analogue to base flow index was derived by averaging the time series of base and total flow and calculating base flow index as the ratio of the averages. An analogue to base flow recession was derived by averaging the times series of base flow during the high flow months of March and April and during the low flow months of July through September and calculating recession as the ratio of the averages. The results of this exercise are shown in Figure 8.



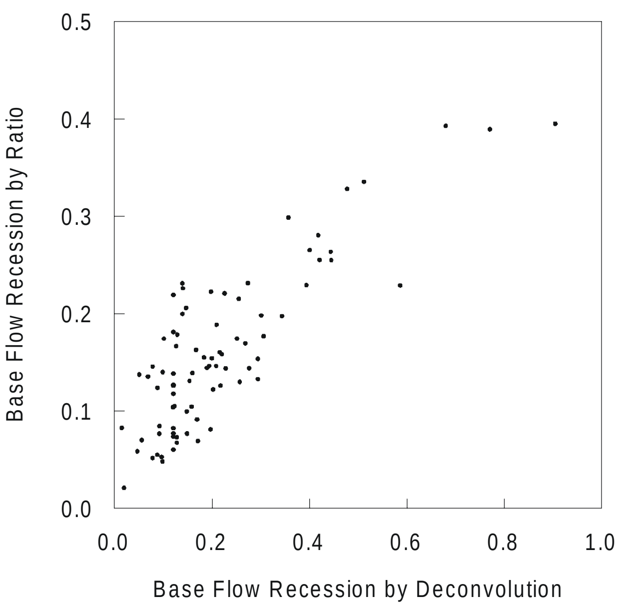


Figure 8. Base flow index (top) and recession (bottom) determined by deconvolution and ratio.

The upper plot compares the values of base flow index determined by deconvolution to the analogue values determined by ratio. The two sets of results compare very closely and confirm the calculation of base flow index using both methods. The lower plot compares the values of base flow recession. A relation between the two sets of results is apparent where, as expected, the values determined by ratio are consistently less than the values determined by deconvolution.

6. RELATION TO PHYSIOGRAPHY

Databases of physiographic parameters were assembled and compared to the selected values of base flow index and recession using correlation analysis in order to assess the suggested relation of groundwater conditions to physiography. The parameters used in this analysis include, for each sub-watershed, the average slope of the ground surface; the fraction of the sub-watershed that is occupied by wetlands and lakes; drainage density measured in terms of the combined lengths and perimeters of wetlands, lakes, and rivers relative to the area of the sub-watershed; the fraction of the sub-watershed that is occupied by hummocky topography (i.e., areas of irregular relief and poorly developed drainage); the thickness and texture of the overburden where texture is measured in terms of the thickness of coarse materials (e.g., sand and gravel) relative to the combined thickness of coarse and fine materials (e.g., silt and clay); and the texture of the bedrock measured in terms of the thickness of coarse materials (e.g., sandstone, limestone, and dolostone) relative to the combined thickness of coarse and fine materials (e.g., shale). The results of the correlation analysis are summarized in Table 1.

Table 1. Correlation of base flow index and recession to physiographic factors.

Physiographic factor	Base flow index	Base flow recession
Slope of the ground surface	0.59	0.55
Wetlands and lakes	0.27	-0.02
Drainage density	-0.15	-0.06
Hummocky topography	0.08	0.16
Thickness of the overburden	-0.23	0.04
Texture of the overburden	0.70	0.40
Texture of the bedrock	0.19	-0.28

Base flow index and recession are both related to the slope of the ground surface. This indicates that adequate incision of surface water features into the landscape is required to enable groundwater discharge, and to ensure that discharge persists as groundwater levels decline. Base flow index is also related to the extent of wetlands and lakes. These features provide storage capacity for flow and resistance to drainage which, in combination, buffer stream flow. These features therefore generate a stream flow signature that is similar to the signature of groundwater discharge. The relatively weak relation of base flow index to drainage density is intuitive; drainage density necessarily increases in areas where runoff is the primary mechanism of drainage. Base flow index is distinctly related to the texture of the overburden and, to a lesser extent, to the thickness of the overburden and texture of the bedrock. Resistance to groundwater recharge measured in terms of the permeability, storativity, and thickness of the overburden and the permeability of the bedrock may be a factor regulating groundwater conditions. In areas where this resistance is large, groundwater levels rise toward the ground surface more rapidly and runoff becomes the primary mechanism of drainage.

Base flow recession has a weak relation to the extent of hummocky topography that may be the result of the poorly developed drainage. Base flow recession is also related to the texture of the overburden and bedrock and increases as the texture of the overburden increases and as the texture of bedrock decreases. Transient groundwater flow processes progress more slowly in areas of elevated storativity associated within coarse textured overburden and in areas of diminished permeability associated with finer textured, lower permeability bedrock. This results in more persistent groundwater discharge and larger values of base flow recession.

7. CONCLUSIONS

Groundwater is an important water supply across southern Ontario and has a simultaneous and equally important role in the maintenance of in-stream conditions and aquatic habitat. Groundwater conditions measured in terms of base flow - the discharge of groundwater to wetlands, lakes, and rivers - vary spatially and in response to climate. The dynamics of the interaction of groundwater and climate were determined for a study area that extends over south-central and southwestern Ontario. The spatial component of this variation is the result of physiographic factors such as terrain and characteristics of the overburden and bedrock. Physiography can therefore be used to estimate groundwater conditions in areas where direct determination is not otherwise feasible, and may also be useful in guiding land and water use management. In general, groundwater conditions are most favorable in areas that are characterized by significant incision of wetlands, lakes, and rivers into the landscape and by coarse textured overburden and bedrock of modest permeability. The availability of precipitation in excess of abstractions such as evapo-transpiration and changing soil moisture for partitioning into surface runoff and groundwater recharge fluctuates on an annual cycle and in response to climate variability and change. Runoff responds rapidly to precipitation while the base flow response may persist for several to many months. In a majority of sub-watersheds, base flow can be reasonably accurately estimated as the convolution of a response function and time series of runoff. Base flow index and recession are the parameters of the response function and measure the average rate of groundwater discharge relative to stream flow and the timing of discharge in response to recharge. By defining base flow index and recession using the mathematical formality of convolution, and by estimating values by deconvolution, these parameters are useful both as indicators of groundwater conditions and in modelling the impacts of climate variability and change on these conditions.

8. ACKNOWLEDGMENTS

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9. REFERENCES

Environment Canada 1999. HYDAT Surface water and sediment data. Published on CDROM by Greenland International Consulting, Inc., Concord, Ontario.

Linsley, R.K., Kohler, M.A., and Paulhus, J.L.H. 1982. Hydrology for engineers. McGraw-Hill, New York.

Moin, S.M.A., Southam, C.F., and Brown, D.W. 1998. Mapping groundwater recharge and discharge zones using base flow indicators for the Grand River basin. *In* Proceedings of Groundwater in a Watershed Context, Burlington, Ontario, pp. 203-211.

Natham, R.J., and McMahon, T.A. 1990. Evaluation of automated techniques for base flow and recession analyses. Water Resources Research, 26: 1465-1473.

Piggott, A., Southam, C., Moin, S., and Brown, D. 2000. Determining base flow indicators in west-central Ontario. *In* Proceedings of the First Joint IAH-CNC and CGS Groundwater Specialty Conference, Montreal, Quebec, pp. 233-240.

Press, W.H., Teukolsky, S.A., Vetterling, W.T., and Flannery, B.P. 1992. Numerical recipes in FORTRAN. Cambridge University Press, New York.

Wylie, C.R., and Barrett, L.C. 1982. Advanced engineering mathematics. McGraw-Hill, New York.