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Base flow analysis – a tool in assessing climate change impacts on groundwater resources

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Abstract
As the time scales for various hydrologic components differ by orders of magnitude, it becomes difficult to study the impact of climate change scenarios at local and regional levels. A heuristic method is developed to link hydrologic components to assess impacts related to climate variability by focusing on a large river system in south-central Ontario, Canada. Time series of hydrologic and climatic data for 78 sub-watersheds and 12 climate stations within and surrounding the Grand River watershed in Ontario are employed to characterize the region in terms of base flow index and excess precipitation. Base flow index (defined as base flow relative to total stream flow) varies from 20 percent in areas with extensive deposits of fine textured glaciolacustrine sediments to greater than 80 percent in areas where coarse granular sediments and bedrock occur at the ground surface. Excess precipitation (defined as stream flow relative to precipitation) is greatest during January and February at 90 percent and least during July and August at 10 percent. When plotted as a function of temperature, excess precipitation displays definite hysteresis and is greater during the spring than during the fall, presumably due to antecedent moisture conditions. Combined, these results provide a rational basis for estimating rates of groundwater recharge subject to current climatic conditions and climate change. The importance of contiguous data for various hydrologic components is demonstrated by focusing on information windows with concurrent data sets.

INTRODUCTION

Groundwater is an unseen but an important component of the hydrologic cycle. Groundwater, like all other hydrologic components, is subject to impacts emanating from stresses such as land use changes, increased groundwater withdrawals, extreme dry or wet water supply cycles, etc. An emerging issue is the stress on the groundwater from climate variability and change. While most water resources specialists acknowledge that the relation of groundwater to climate is intuitive, there is a general consensus that relatively little is known about the interaction of climate and groundwater. This limitation in understanding is of concern given the human and ecosystem functions of groundwater. This can be best illustrated from the compiled information of the municipal and potable water supply system in rural and urban centres away from the Great Lakes in Ontario are groundwater dependent. As is well understood, groundwater discharge or baseflow is the primary component to sustain flow in streams and lakes between precipitation and snowmelt events. Thus, various aspects of groundwater movement are critical to the aquatic ecosystem health. Environment Canada, through the Great Lakes 2000 program, is conducting a study of potential impacts of climate change and variability on groundwater conditions within the Grand River basin in west-central Ontario, Canada. This study complements an earlier assessment of impacts on surface water supply and demand (Southam et al., 1997).

The Grand River, a designated Canadian Heritage River, and its three main tributaries, the Conestogo, Nith and Speed Rivers, form the largest watershed in southern Ontario. The watershed drains an area of 6800 km2 and covers 10 counties and regional municipalities and discharges, on an annual basis, more than two billion cubic metres of runoff into Lake Erie. The watershed is characterized by vibrant service, manufacturing, and agricultural economies and an expanding population may exceed one million within the next few decades. All of these sectors are dependent on groundwater where this dependence is likely to be responsive to climate change. Thus, the direct impacts of climate change may be compounded by indirect impacts associated with a conjunctive increase in water use. Historically, the Grand River was prone to both damaging flooding during the spring and poor water quality during the summer. The construction and expert management of a network of multipurpose reservoirs that is distributed across the watershed has proven to be highly effective in minimizing these concerns; however, the impacts of climate change may further stress and challenge this management capacity.

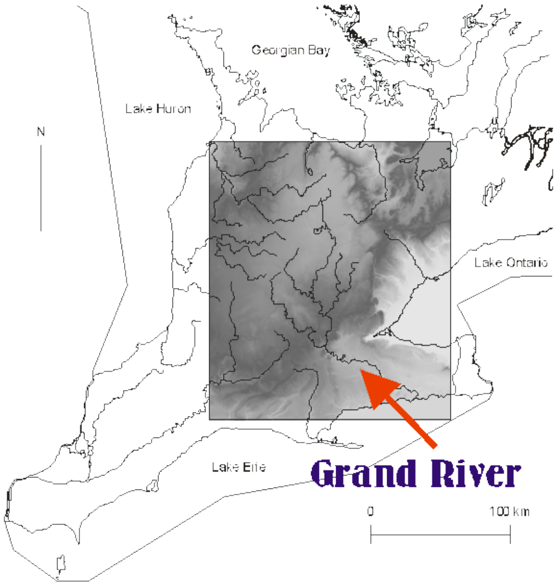
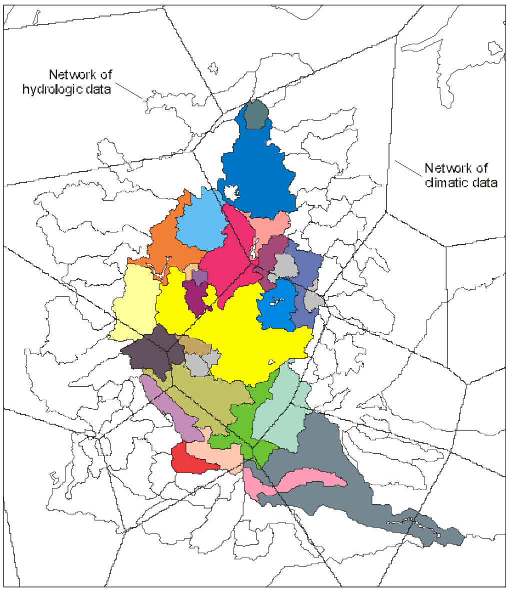


Figure 1. Location and topography of the study area.

Figure 1 indicates the location and topography of the study area. The highlighted region extends 200 km from south to north and 170 km from west to east. The topography of the study area is varied relative to conditions elsewhere in southern Ontario, ranging from an elevation of 75 m above sea level along the shoreline of Lake Ontario to 530 m within the Dundalk Uplands south of Georgian Bay. Figure 2 indicates the networks of sub-watersheds and climate stations that are used in this study. The central, lightly shaded group of sub-watersheds is within the limits of the Grand River watershed and has useful stream flow data.



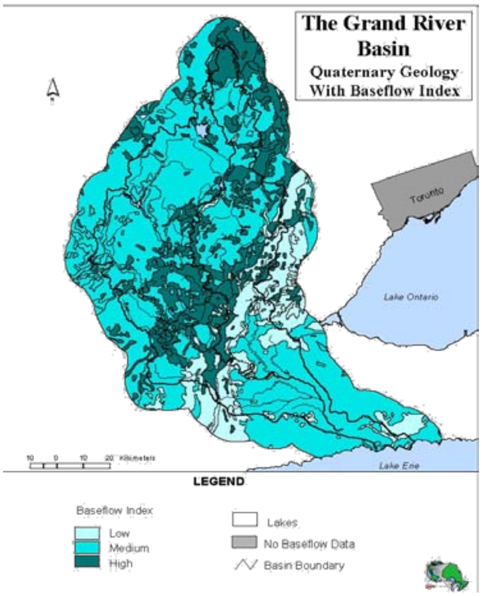


Figure 2. Networks of hydrologic and climatic data. **Figure 3. Map of base flow index (BFI).**

Simplistic hydrologic and climatic factors that are addressed in this. Here, evapotranspiration is assumed to be proportional to precipitation where the constant of proportionality is a function of temperature. Excess precipitation relative to evapotranspiration then forms runoff from the ground surface that immediately contributes to stream flow and also infiltrates into the groundwater flow regime for latter discharge as base flow. Water use, while not explicitly addressed in the following analyses, is also an issue. The net rate of recharge is defined as infiltration minus the portion of water use that is not returned to the groundwater flow regime through a "closed-loop" such wastewater discharge to a septic system.

BASE FLOW ANALYSIS

Base flow analysis forms an important tool for water resources assessment purposes. Traditionally, the base flow is referred to the flow originating and sustaining the streams following the culmination of all surface flow components to the next event. The base flow thus includes stream flow supplied by the groundwater system mostly below the groundwater table. While this information is important, it is absolute in its contents and cannot be generalized or regionalized for assessment purposes. An alternate form of base flow information is derived from a normalized value of base flow volume; This partitioning is represented using base flow index (BFI) where BFI is defined as the average of annual volumes of groundwater discharge, or base flow, calculated for a sub-watershed relative to the corresponding annual volumes of total stream flow for the sub-watershed. BFI is a dimensionless parameter within the range of zero to unity. Earlier investigations by Moin and Shaw (1986) and Moin, et al (1998) demonstrated the utility of BFI. Using the BFI also renders the variable non-dimensional and can to be regionalized. Furthering this logic Moin and Shaw (1986) used BFI as a variable in the regional flow analysis of Ontario streams.

An intricate series of operations is required to determine BFI and only a brief summary of the procedure is reported. Stream flow data for each of the sub-watersheds were obtained and then formatted as time series. These series were input into a relational database and the turning points method of base flow separation was used to extract sets of turning points from the series. These points were then interpolated to form an output time series of base flow that matches the timing of the input series of stream flow. Next, the time series of base and total flow were returned to a database and totaled for each of water years 1971 through 1995 (October 1, 1970 through September 31, 1995). The resulting volumes were differentiated using the topology of the network of sub-watersheds to eliminate upstream flow contributions. BFI values were then calculated for each sub-watershed and water year and averaged over the common period of 1980 to 1989 to obtain a characteristic value for each sub-watershed. Time series of base flow were calculated for all 78 sub-watersheds; however, averaged estimates of BFI for the period of 1980 through 1989 were obtained for only 41 of these sub-watersheds due to discontinuities in the time series and the rejection of sub-watersheds where significant flow regulation is known to occur. The period of 1980 through 1989 was selected such that a near-optimal number of averaged results were obtained.

The output values of BFI vary from a minimum of 0.2, indicating only a modest contribution of groundwater discharge to total stream flow, to a maximum of 0.86, indicating a very substantial contribution. These values were classified into the categories of low (0.0 to 0.3), moderate (0.3 to 0.5), and high (0.5 to 1.0) that are indicated in Figure 3. Sub-watersheds that are not shaded in Figure 3 either lack sufficient data to form an average or are subject to flow regulation. Preliminary results of these analyses indicate that Quaternary geology is a leading factor in the generation of base flow, with the smallest values of BFI observed in areas that are characterized by fine textured glaciolacustrine sediments and the largest values observed in areas where coarse granular sediments and bedrock occur at the ground surface.

HYDROLOGIC AND CLIMATIC CHARACTERIZATION

In order to relate the impact of climate variability on groundwater a series of analyses was carried out. As a first step the total precipitation was divided into two components, total losses and total runoff. The losses consist of evapotranspiration, consumptive uses and deeper groundwater recharge, while the runoff had two sub-components of surface runoff and baseflow volumes. The calculations that were conducted in the exercise described in the previous section yielded time series of baseflow at a daily time step for the period between 1980 and 1989. As a next step three sets of watersheds were selected representing the three ranges of BFI from low, moderate to high. From data continuity considerations only two stations in each BFI group within the Grand River basin were chosen. These were Blue Springs Creek (0.75) and Eramosa River (0.63) with high BFI, Fairchild (0.45) and McKenzie (0.42) Creeks in the moderate BFI and the Conestogo (0.27) and Nith (0.21) Rivers in the low BFI values. Daily baseflow for these streams were integrated on a monthly basis. This yielded ten values of baseflow volumes and BFI on a monthly basis. The monthly values were averaged to yield an annual cycle of BFI variation for the three categories of hydrologic response units.

The objective of this second series of calculations is to estimate monthly excess precipitation as the proportion of precipitation that is not lost to evapotranspiration. This is accomplished by determining runoff on a monthly basis, adjusting this value to include infiltration, and comparing the result to precipitation. It is necessary to perform the calculation of flow using only runoff due to the contrasting time scales of surface and groundwater discharge. Inspection of the climatic and stream flow data suggests that surface water discharge in response to a precipitation event has a time scale of several days, and therefore that the runoff observed during a particular month is largely a function of the precipitation that occurred during that month. In contrast, groundwater discharge in response to a precipitation event has a time scale of many months, and therefore the base flow observed during a particular month is a function of the precipitation that occurred during many previous months.

Daily time series of mean temperature and total precipitation data for 57 climate stations located within southwestern and south-central Ontario were obtained and were assessed for completeness of record during the period of water years 1971 through 1995. A total of 12 stations with adequately complete records of these data elements were identified within and surrounding the Grand River watershed. The geometry of this network is shown in Figure 2. The degree day method was then used to adjust the records of total precipitation for snow accumulation and melting, yielding 12 time series of the daily volume of water released at the ground surface due to precipitation and snow melting.

Sub-watersheds were selected from the network shown in Figure 2 such that each has a tributary area of between 100 and 1000 km^2, has a relatively complete record of stream flow data during the period of water years 1971 through 1995, and is not subject to flow regulation. This selection process resulted in a list of 17 sub-watersheds. Runoff from each of the 17 sub-watersheds and 12 months of the year was determined by subtracting base flow from stream flow using the time series of data that were developed during the hydrologic characterization exercise, averaging the difference over each month, adjusting the average to include infiltration using the calculated value of BFI for the sub-watershed, and distributing the average over the area of the sub-watershed. The adjustment applied to the runoff data assumes that the partitioning of excess precipitation into runoff and infiltration is constant throughout the year. Daily precipitation adjusted for snow accumulation and melting, for each of the climate stations was similarly averaged over each month and then spatially averaged over each sub-watershed to determine the total input into the sub-watersheds. Monthly values of excess precipitation were calculated as flow divided by precipitation and plotted for each sub-watershed. The resulting 17 plots were examined and a set of six sub-watersheds with consistent behaviours was identified. In particular, sub-watersheds in which flows during the winter months significantly exceeded precipitation and snow melting were assumed to reflect anthropogenic contributions such as discharge from wastewater treatment plants and were discarded. The resulting BFI information for the three categories is shown in Figure 3.

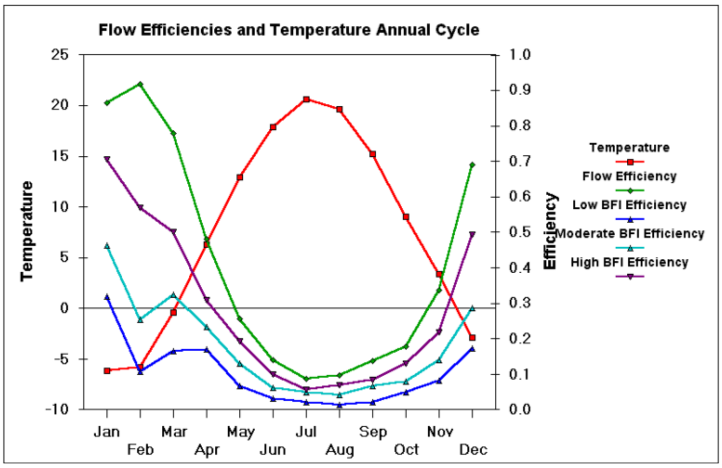


Figure 4. Annual variation of monthly average excess precipitation, baseflow and temperature.

These six sets of excess precipitation data, average values of base flow for the three BFI responses and the corresponding plots of average temperature are shown in Figure 4. Excess precipitation exhibits a distinct annual pattern with maximum values of roughly 90 percent occurring during January and February and minimum values of 10 percent occurring July and August. For most part the base flow mimics the excess precipitation pattern, except for a reversal in January and February indicating the below freezing temperatures and the nature of base flow. The points shown for each month indicate the values calculated for the six sub-watersheds and the solid line indicates the simple average of these values. There is relatively little scatter among the data for each month, particularly during the summer, and therefore the use of averaged values appears to be justifiable. The plot of temperature exhibits the expected annual pattern, again with very little scatter among the values for the selected sub-watersheds. Minimum and maximum temperatures occur during January and July, respectively, and freezing conditions persist from mid December through mid March.

GROUND AND SURFACE WATER EFFICIENCIES

In order to develop the tools for evaluating climate change impact, it was necessary to establish a template for basin response based on the groundwater characteristics. Figure 5 illustrates the averaged data shown in Figure 4 where normalized excess precipitation and baseflow are plotted as a function of temperature. The plot displays distinct hysteresis with consistently higher values of excess precipitation and baseflow occurring during months that are characterized by increasing temperatures, February through July or the drying limb of the hysteresis, than during months that are characterized by decreasing temperatures, August through January or the wetting limb of the hysteresis. This hysteresis may be due to varying antecedent soil moisture conditions and possibly also reduced plant use of water during the spring relative to the fall. Hysteresis is limited during the months of June through September, presumably due to the reduced variability of these factors. The extent of the hysteresis indicates that the approximation of evapotranspiration for current climatic conditions, and for climate change scenarios, must be based on both the magnitude and trend of temperature.

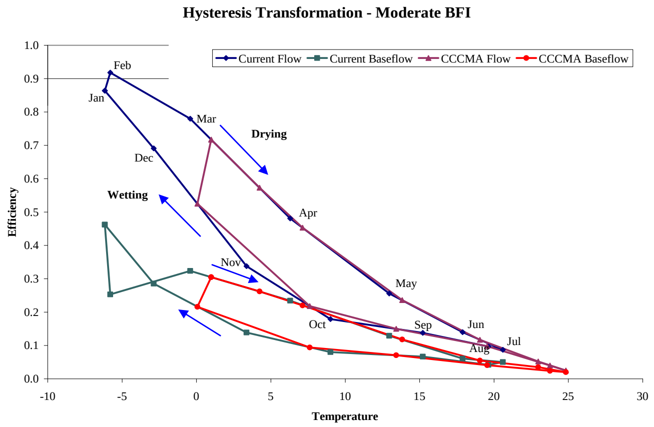


Figure 5. Monthly average excess precipitation and baseflow as a function of temperature.

At least two issues that are pertinent to the relation of groundwater to climate, and to the potential impacts of climate change, may be inferred from Figure 5. First, it is obvious that precipitation events that occur during the summer months result in limited excess precipitation and therefore are less effective in replenishing groundwater resources. Thus, any climate change related shift toward increased precipitation during the summer due to increased convective activity would have only a limited benefit from the perspective of water supply. Second, the highest values of excess precipitation occur during the months of December through March when temperatures are below freezing.

CLIMATE CHANGE MODELS

Several generations of global circulation models (GCM) and coupled circulations models (GCCM) exist for assessing the impact of climate change. These models consider the heating of the atmosphere in presence of increased amounts of carbon dioxide and other aerosols. There are five different models that have undergone significant of development, testing and inter-comparisons. These models were originally developed in Australia, Canada, Germany, USA and UK. For this study the general circulation models from the Canadian Climate Centre Modelling and Analysis (CCCMa) group and UK's Hadley model were selected for analysis. For these two models three time slices were chosen to represent 1.5 times the CO_2 level, doubling and tripling of CO_2. These were represented by the climate sequences obtained by considering 20-year averages. The critical years were 2030 for 1.5 times CO_2, 2050 for doubling and 2090 for tripling. Again for brevity the extreme results for CCCMa for 2090 are presented in this paper. The salient statistics of 2090 climate compared to the model generated current climate are noted in Table 1. It should be noted that other than temperature that are absolute departures all other variables are presented in a ratio of current climate.

Table 1.CCCMA 2090 Climate Estimates for Grand River Basin.

Variable	Mean Change	Range of Change
Cloud cover	1.04	1.17 in February to 0.95 in December
Evaporation	1.32	2.33 in February to 0.58 in December
Precipitation	1.11	1.36 in March to 0.93 in August
Incident solar radiation	0.95	0.89 in February to 1.00 in December
Mean screen temperature	5.64	10.04 in February to 2.93 in December
10-m wind	0.96	1.14 in April to 0.79 in December

IMPACT ANALYSIS

The template described above was employed in assessing the impact of climate change on surface and groundwater resources. It was postulated that in a climate change scenario with the increase in the mean screen temperature, the interaction of surface and ground water and other losses would follow along the wetting and drying limbs of the hysteresis exhibited in Figure 5. Thus in the new climate regime the hydrologic functions, in February for example, would behave more like in March-April time frame. Also the accumulation of precipitation as snow will not exist and precipitation will be available for runoff. For the climate change impact, therefore, the efficiency curves (hysteresis) were shifted along the original curves and values interpolated and extended for the summer months. This exercise was also repeated for the three BFI response efficiency curves as well. The impact of climate change on the overall availability of water is shown in the two spider-graphs in Figure 6. The flow components divided into total available water as precipitation, total observed runoff and groundwater flow are shown for the current climate regime and for CCCMA 2090 scenario with High BFI response units. This visualization helps understand the changes in the distribution of moisture, the degree of impact on the total runoff and groundwater flows.

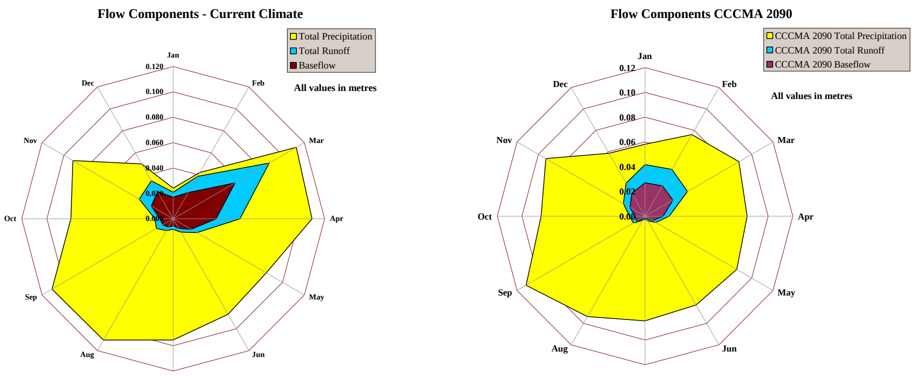


Figure 6. Impact of climate change on flow components for Moderate BFI response in 2090.

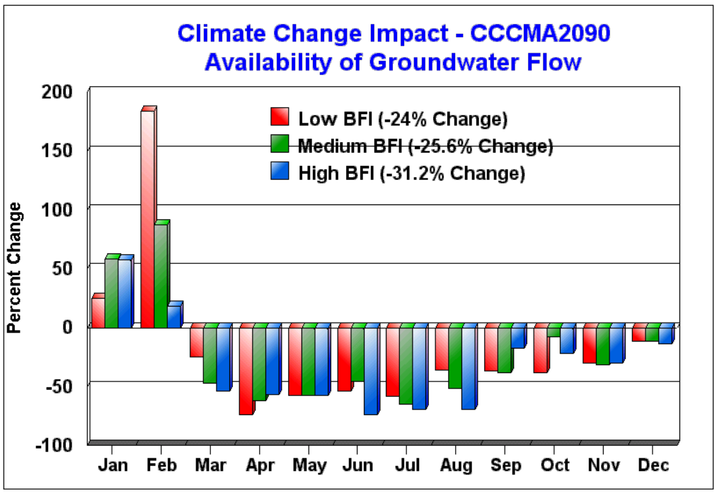


Figure 7. Change in the availability of groundwater flow under climate stresses.

For the three types of BFI soils analyzed, the influence of climate change is summarized in Figure 7. There is a common theme in all three, although the magnitudes differ, that the climate change will likely bring substantial differences in flow regimes. For example, there will be more flow likely in January and February and much less at other times. The overall reductions are –24% for soils with low BFI, -25.6% for moderate BFI and –31.2% for high BFI soils. These values are similar to the volumetric impact on the surface flow or total available runoff. Also, the total runoff from the watershed decreases from 348 mm annually to 240 mm or a change of –31.2%. Similar statistics exist for baseflow components.

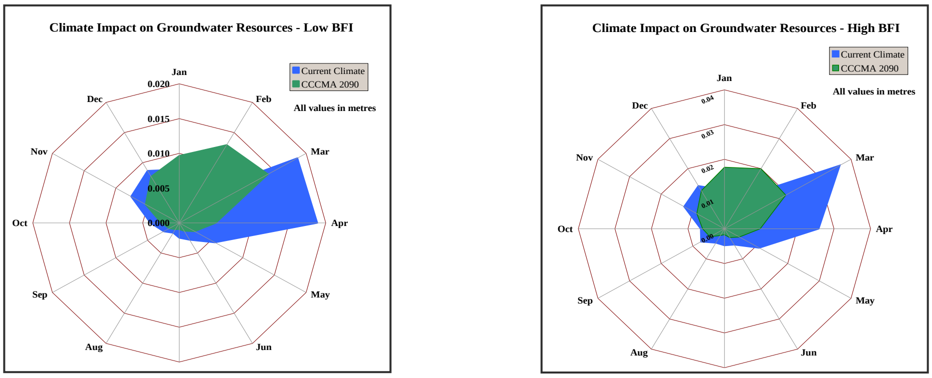


Figure 8. Impact on groundwater resources between current climate and CCCMA 2090.

The hydrologic and climatic characterization results indicate that groundwater availability is not uniform across the study area under current climatic conditions and that, because excess precipitation and groundwater flow are function of climate, climate change may lead to a reduction in the availability of groundwater. For example, groundwater levels and discharge may decline throughout the year due to an overall reduction in excess precipitation. Larger declines may occur during the late winter and early spring due to reduced snow accumulation and melting and increased evapotranspiration. It is also possible that groundwater quality concerns may extend over larger areas if infiltration is reduced in response to climate change.

It is important to note that the results that are reported in this paper were derived for a relatively small sample of sub-watersheds; for example, estimates of BFI were developed for only 41 of the 78 watersheds that were initially selected for analysis. Thus, the full range of BFI values may be under represented and the relation of BFI to Quaternary geology may be unreliable. Similarly, the hysteresis of excess precipitation was developed using data for only six sub-watersheds, all of which are located within the lower to middle portions of the watershed and are subject to climatic and land and water use factors that may not be representative of the entire watershed. Analysis of a larger sample of sub-watersheds that extend further beyond the limits of the Grand River watershed, where flow regulation is more commonly applied than elsewhere in southwestern Ontario, may resolve or at least minimize these uncertainties.

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