Base Flow Due to Groundwater Discharge

Indicator #7102

Overall Assessment

Status:	**Mixed**
Trend:	**Deteriorating**
Rationale:	**It is estimated that human activities have detrimentally impacted groundwater discharge on at least a local scale in some areas of the Great Lakes basin and that discharge is not significantly impaired in other areas.**

Lake-by-Lake Assessment

Each lake was categorized with a not assessed *status and an* undetermined *trend, indicating that assessments were not made on an individual lake basis.*

Purpose

- To measure the contribution of base flow due to groundwater discharge to total stream flow
- To detect the impacts of anthropogenic factors on the quantity of the groundwater resource

Ecosystem Objective

Base flow due to the discharge of groundwater to the rivers and inland lakes and wetlands of the Great Lakes basin is a significant and often major component of stream flow, particularly during low flow periods. Base flow frequently satisfies flow, level, and temperature requirements for aquatic species and habitat. Water supplies and the capacity of surface water to assimilate wastewater discharge are also dependent on base flow. Base flow due to groundwater discharge is therefore critical to the maintenance of water quantity and quality and the integrity of aquatic species and habitat.

State of the Ecosystem

Background

A significant portion of precipitation over the inland areas of the Great Lakes basin returns to the atmosphere by evapo-transpiration. Water that does not return to the atmosphere either flows across the ground surface or infiltrates into the subsurface and recharges groundwater. Some of this water is subsequently removed by consumptive uses such as irrigation and water bottling. Water that flows across the ground surface discharges into surface water features (rivers, lakes, and wetlands) and then flows toward and eventually into the Great Lakes. The component of stream flow due to runoff from the ground surface is rapidly varying and transient, and results in the peak discharges of a stream.

Water that infiltrates into the subsurface and recharges groundwater also results in flow toward the Great Lakes. Most recharged groundwater flows at relatively shallow depths at local scales and discharges into adjacent surface water features. However, groundwater also flows at greater depths at regional scales and discharges either directly into the Great Lakes or into distant surface water features. The quantities of groundwater flowing at these greater depths can be significant locally but are generally believed to be modest relative to the quantities flowing at shallower depths. Groundwater discharge to surface water features in response to precipitation is greatly delayed relative to surface runoff. The stream flow resulting from groundwater discharge is, therefore, more uniform.

Base flow is the less variable and more persistent component of total stream flow. In the Great Lakes region, groundwater discharge is often the dominant component of base flow. However, various human and natural factors also contribute to base flow. Flow regulation, the storage and delayed release of water using dams and reservoirs, creates a stream flow signature that is similar to that of groundwater discharge. Lakes and wetlands also moderate stream flow, transforming rapidly varying surface runoff into more slowly varying flow that approximates the dynamics of groundwater discharge. It is important to note that these varying sources of base flow affect surface water quality, particularly with regard to temperature. All groundwater discharge contributes to base flow but not all base flow is the result of groundwater discharge.

Status of Base Flow

Base flow is frequently determined using a mathematical process known as hydrograph separation. This process uses stream flow monitoring information as input and partitions the observed flow into rapidly and slowly varying components, i.e., surface runoff and base flow, respectively. The stream flow data that are used in these analyses are collected across the Great Lakes basin using networks of stream flow gauges that are operated by the United States Geological Survey (USGS) and Environment Canada. Neff *et al*. (2005) summarize the calculation and interpretation of base flow for 3,936 gauges in Ontario and the Great Lakes states using six methods of hydrograph separation and length-of-record stream flow monitoring information for the periods ending on December 31, 2000 and September 30, 2001, respectively. The results reported by Neff *et al*. (2005) are the basis for the majority of this report. Results corresponding to the United Kingdom Institute of Hydrology (UKIH) method of hydrograph separation (Piggott *et al*. 2005) are referenced throughout this report in order to maintain consistency with the previous report for this indicator. However, results calculated using the five other methods are considered to be equally probable outcomes. Figure 1 illustrates the daily stream flow monitoring information and the results of hydrograph separation for the Nith River at New Hamburg, Ontario, for January 1 to December 31, 1993. The rapidly varying response of stream flow to precipitation and snow melt are in contrast to the more slowly varying base flow.

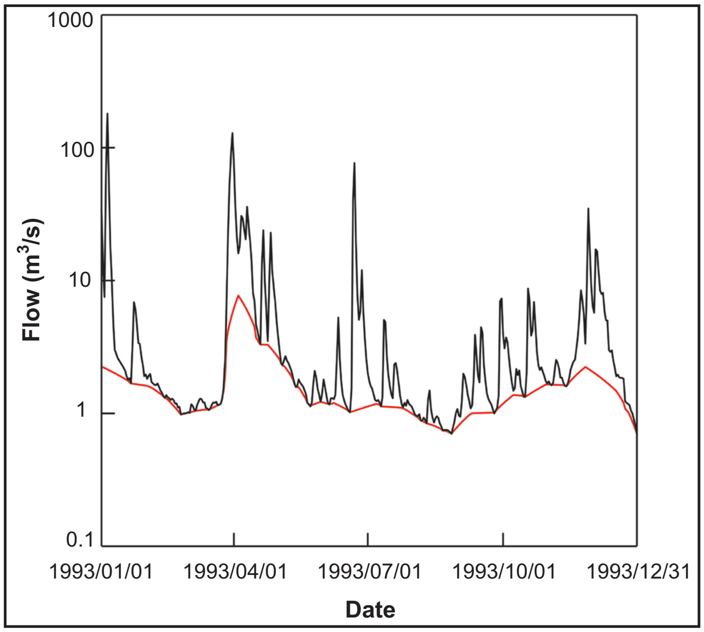

Figure 1. Hydrograph of observed total stream flow (black) and calculated base flow (red) for the Nith River at New Hamburg during 1993.
Source: Environment Canada and the U.S. Geological Survey

Application of hydrograph separation to daily stream flow monitoring information results in lengthy time series of output. Various measures are used to summarize this output. For example, base flow index is a simple, physical measure of the contribution of base flow to stream flow that is appropriate for use in regional scale studies. Base flow index is defined as the average rate of base flow relative to the average rate of total stream flow, is unitless, and varies from zero to one where increasing values indicate an increasing contribution of base flow to stream flow. The value of base flow index for the data shown in Figure 1 is 0.28, which implies that 28% of the observed flow is estimated to be base flow. Neff *et al*. (2005) used a selection of 960 gauges in Ontario and the Great Lakes states to interpret base flow. Figure 2 indicates the distribution of the values of base flow index calculated for the selection of gauges relative to the gauged and ungauged portions of the Great Lakes basin. The variability of base flow within the basin is apparent. However, further processing of the information is required to differentiate the component of base flow that is due to groundwater discharge and the component that is due to delayed flow through lakes and wetlands upstream of the gauges. An approach to the differentiation of base flow calculated using hydrograph separation into these two components is summarized in the following paragraphs of this report. Variations in the density of the stream flow gauges and discontinuities in the coverage of monitoring are also apparent in Figure 2 and may have significant implications relative to

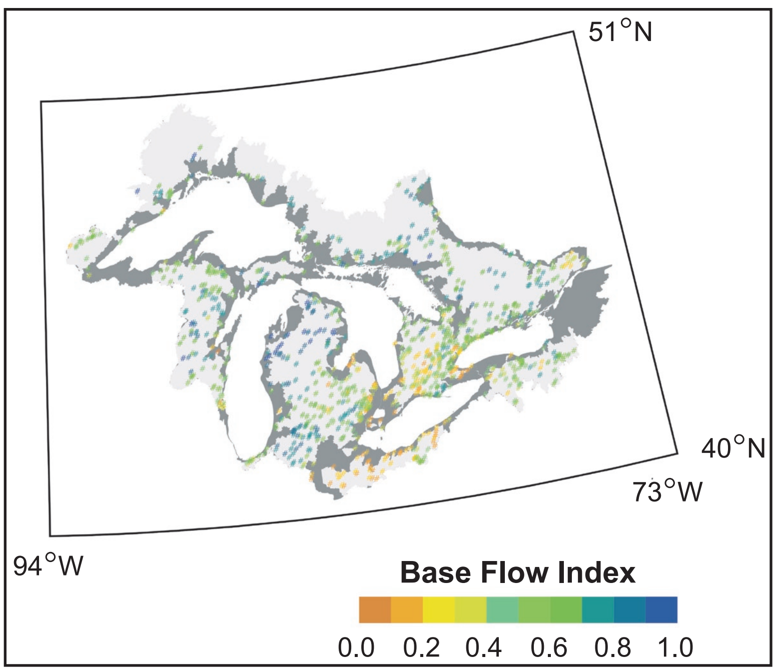

Figure 2. Distribution of the calculated values of base flow index relative to the gauged (light grey) and ungauged (dark grey) portions of the Great Lakes basin.
Source: Environment Canada and the U.S. Geological Survey

the interpretation of base flow.

The values of base flow index calculated for the selection of gauges using hydrograph separation are plotted relative to the extents of surface water upstream of each of the gauges in Figure 3. The extents of surface water are defined as the area of lakes and wetlands upstream of the gauges relative to the total area upstream of the gauges. While there is considerable scatter among the values, the expected tendency for larger values of base flow index to be associated with larger extents of surface water is confirmed. Neff *et al.* (2005) modeled base flow index as a function of surficial geology and the spatial extent of surface water. Surficial geology is assumed to be responsible for differences in groundwater discharge and is classified into coarse and fine textured sediments, till, shallow bedrock, and organic deposits.

The modeling process estimates a value of base flow index for each of the geological classifications, calculates the weighted averages of these values for each of the gauges based on the extents of the classifications upstream of the gauges, and then modifies the weighted averages as a function of the extent of surface water upstream of the gauges. A non-linear regression algorithm was used to determine the values of base flow index for the geological classifications and the parameter in the surface water modifier that correspond to the best match between the values of base flow index calculated using hydrograph separation and the values predicted using the model. The process was repeated for each of the six methods of hydrograph separation.

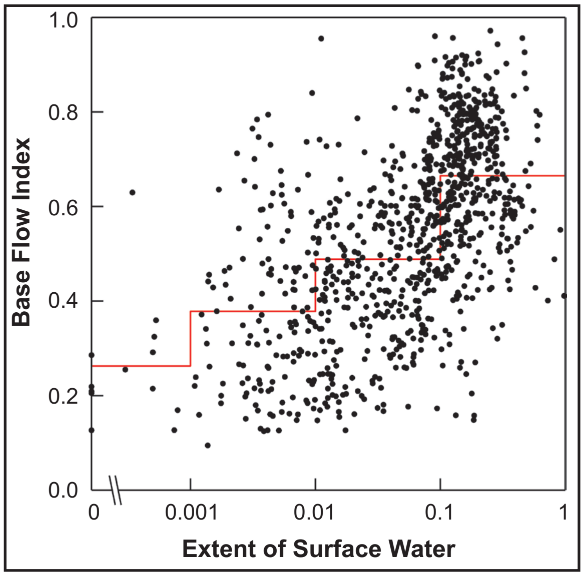

Figure 3. Comparison of the calculated values of base flow index to the corresponding extents of surface water.

The step plot (red) indicates the averages of the values of base flow index within the four intervals of the extent of surface water.

Source: Environment Canada and the U.S. Geological Survey

Extrapolation of base flow index from gauged to ungauged watersheds was performed using the results of the modeling process. The ungauged watersheds consist of 67 tertiary watersheds in Ontario and 102 eight-digit hydrologic unit code (HUC) watersheds in the Great Lakes states. The extents of surface water for the ungauged watersheds are shown in Figure 4 where the ranges of values used in the legend match those used to average the values of base flow index shown in Figure 3. A component of base flow due to delayed flow through lakes and wetlands appears to be likely over extensive portions of the Great Lakes basin. The distribution of the classifications of geology is shown in Figure 5. Organic and fine textured sediments are not differentiated in this rendering of the classifications because both classifications have estimated values of base flow index due to groundwater discharge in the range of 0.0 to 0.1. However, organic deposits are of very limited extent and represent, on average, less than 2% of the area of the ungauged watersheds. The spatial variation of base flow index shown in Figure 5 resembles the variation shown in Figure 2. However, it is important to note that the information shown in Figure 2 includes the influence of delayed flow through lakes and wetlands upstream of the gauges while this influence has been removed, or at least reduced, in the information shown in Figure 5.

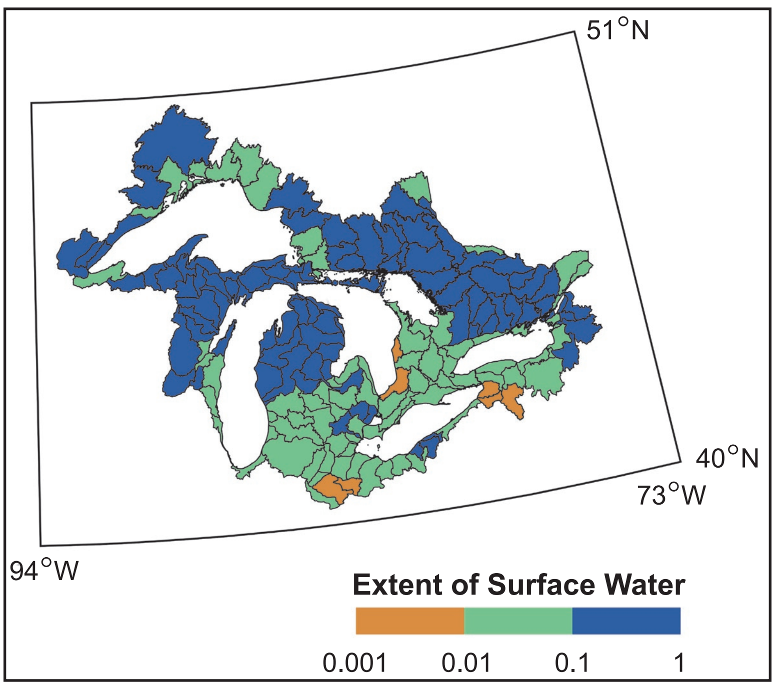

Figure 4. Distribution of the extents of surface water for the ungauged watersheds.

Source: Environment Canada and the U.S. Geological Survey

Figure 6 indicates the values of the geological component of base flow index for the ungauged watersheds obtained by calculating the weighted averages of the values for the geological classifications that occur in the watersheds. This map therefore represents an estimate of the length-of-record contribution of base flow due to groundwater discharge to total stream flow that is consistent and seamless across the Great Lakes basin. The pie charts indicate the range of values of the geological component of base flow index for the six methods of hydrograph separation averaged over the sub-basins of the Great Lakes. Averaging the six values for each of the sub-basins yields contributions of base flow due to groundwater discharge of approximately 60% for Lake Huron, Lake Michigan, and Lake Superior and 50% for Lake Erie and Lake Ontario. There is frequently greater variability of this contribution within the sub-basins than among the sub-basins as the result of variability of geology that is more uniformly averaged at the scale of the sub-basins.

Mapping the geological component of base flow index, which is assumed to be due to groundwater discharge, across the Great Lakes basin in a consistent and seamless manner is an important accomplishment in the development of this indicator. Additional information is, however, required to determine the extent to which human activities have impaired groundwater discharge. There are various alternatives for the generation of this information. For example, the values of base flow index calculated for the selection of stream flow gauges using hydrograph separation can be compared to the corresponding modeled values. If a calculated value is less than a modeled value, and if the difference is not related to the limitations of the modeling process, then base flow is less than expected based on physiographic factors and it is possible that discharge has been impacted by human activities. Similarly, if a calculated value is greater than a modeled value, then it is possible that the increased base flow is the result of human activities such as flow regulation and wastewater discharge. Time series of base flow can also be used to assess these impacts. The previous report for this indicator illustrated the detection of temporal change in base flow using data for watersheds with approximately natural stream flow and with extensive flow regulation and urbanization. However, no attempt has yet been made to systematically assess change at the scale of the Great Lakes basin. Change in base flow over time may be subtle and difficult to quantify (e.g., variations in the relation of base flow to climate) and may be continuous (e.g., a uniform increase in base flow due to aging water supply infrastructure and increasing conveyance losses) or discrete (e.g., an abrupt reduction in base flow due to a new consumptive water use). Change may also be the result of cumulative impacts due to a

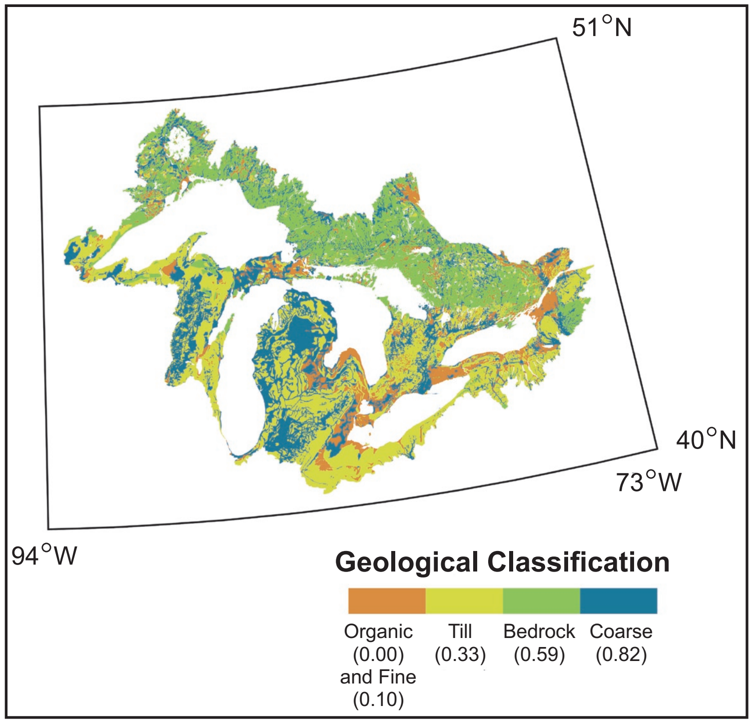

Figure 5. Distribution of the geological classifications.

The classifications are shaded using the estimated values of the geological component of base flow index shown in parentheses.

Source: Environment Canada and the U.S. Geological Survey

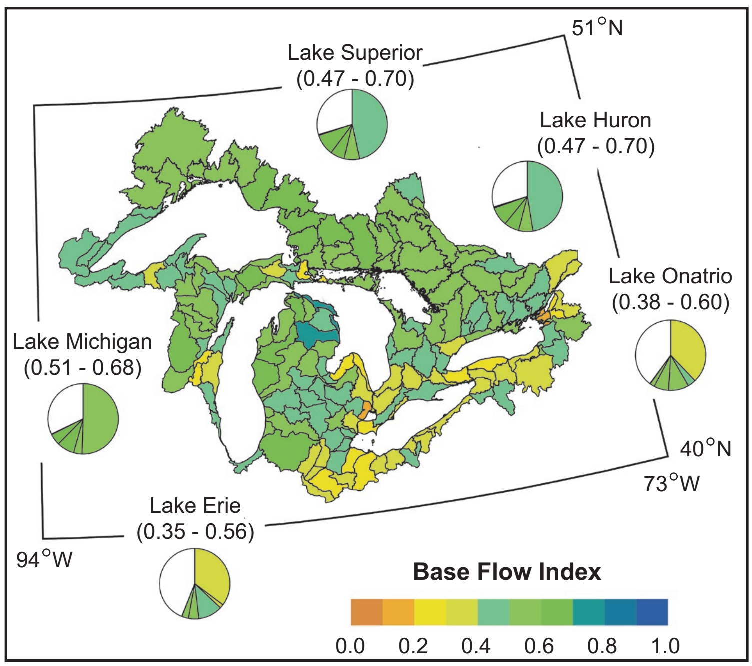

Figure 6. Distribution of the estimated values of the geological component of base flow index for the ungauged watersheds.

The pie charts indicate the estimated values of the geological component of base flow index for the Great Lakes sub-basins corresponding to the six methods of hydrograph separation. The charts are shaded using the six values of base flow index and the numbers in parentheses are the range of the values.

Source: Environment Canada and the U.S. Geological Survey

range of historical and ongoing human activities, and may be more pronounced and readily detected at local scales than at the scales that are typical of continuous stream flow monitoring.

Figure 7 is an alternative view of the data for the Grand River at Galt, Ontario, that was previously used to illustrate the impact of flow regulation on base flow. The cumulative depth of base flow calculated annually as the total volume of flow at the location of the gauge during each year divided by the area that is upstream of the gauge, is plotted relative to cumulative total flow. Base flow index is, by definition, the slope of the accumulation of base flow relative to the accumulation of total flow. The change in slope and increase in base flow index from a value of 0.45 prior to the construction of the reservoirs that are located upstream of the gauge to 0.57 following the construction of the reservoirs clearly indicates the impact of active flow regulation to mitigate low and high flow conditions. Calculating and interpreting diagnostic plots such as Figure 7 for hundreds to thousands of stream flow gauges in the Great Lakes basin will be a large and time consuming, but perhaps ultimately necessary, task.

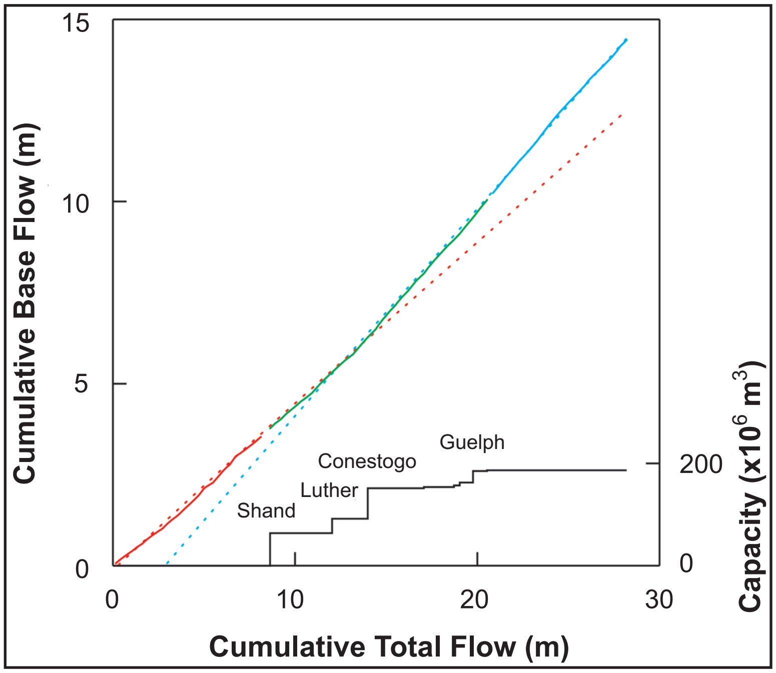

Figure 7. Cumulative base flow as a function of cumulative total flow for the Grand River at Galt prior to (red), during (green), and following (blue) the construction of the reservoirs that are located upstream of the stream flow gauge.

The step plot indicates the cumulative storage capacity of the reservoirs where the construction of the largest four reservoirs is labeled. The dashed red and blue lines indicate uniform accumulation of flow based on data prior to and following, respectively, the construction of the reservoirs.

Source: Environment Canada and the U.S. Geological Survey

Improving the spatial resolution of the current estimates of base flow due to groundwater discharge would be beneficial in some settings. For example, localized groundwater discharge has important implications in terms of aquatic habitat and it is unlikely that this discharge can be predicted using the current regional estimates of base flow. The extrapolation of base flow information from gauged to ungauged watersheds described by Neff *et al.* (2005) is based on a classification and therefore reduced resolution representation of the Quaternary geology of the basin. Figure 8 compares this classification to the full resolution of the available 1:1,000,000 scale (Ontario Geological Survey (OGS) 1997) and 1:50,000 scale (OGS 2003) mapping of the geology of the gauged portion of the Grand River watershed in southern Ontario. Interpretation of base flow in terms of these more detailed descriptions of geology, where feasible relative to the network of stream flow gauges, may result in an improved estimate of the spatial distribution of groundwater discharge for input into functions such as aquatic habitat management.

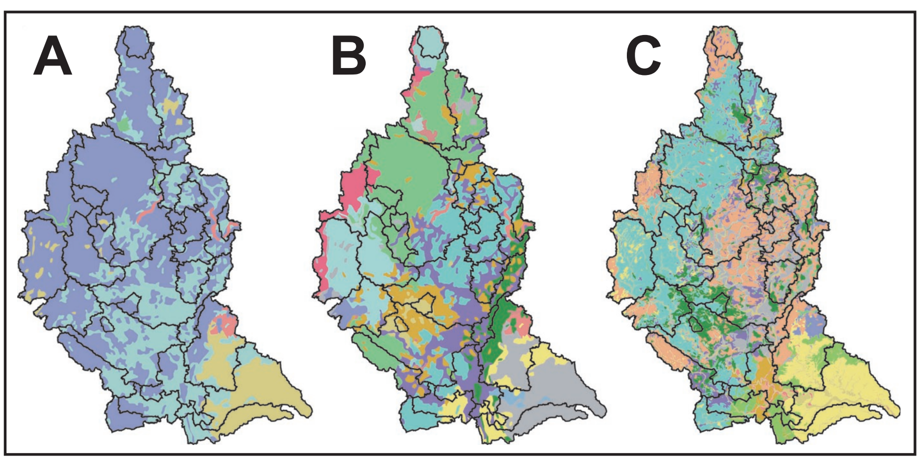

Figure 8. Geology of the gauged portion of the Grand River watershed based on the classification (A) and full resolution (B) of the 1:1,000,000 scale Quaternary geology mapping and the full resolution of the 1:50,000 scale Quaternary geology mapping (C) where random colors are used to differentiate the various geological classifications and units.

Source: Environment Canada and the U.S. Geological Survey

Estimation of base flow using low flow

observations, single "spot" measurements of stream flow under assumed base flow conditions, is another means of improving the spatial resolution of the current prediction of groundwater discharge. Figure 9 illustrates a series of low flow observations performed within the watershed of Duffins Creek above Pickering, Ontario, where the observations are standardized using continuous monitoring information and the drainage areas for the observations following the procedure described by Gebert *et al*. (2005) and then classified into 3-quantile groupings of high, intermediate, and low values. The standardized values of low flow illustrate the spatially variable pattern of groundwater discharge that results from the interaction between surficial geology, the complex three-dimensional hydrostratigraphy, topography, and surface water features. Areas of potentially high groundwater discharge may have particularly important implications in terms of aquatic habitat for cold water fish species such as brook trout.

Finally, reconciling estimates of base flow generated using differing methods of hydrograph separation, perhaps by interpreting the information in a relative rather than absolute manner, will improve the certainty and therefore performance of base flow as an indicator of groundwater discharge. It may also be possible to assess the source of this uncertainty using chemical and isotopic data in combination with the methods of hydrograph separation if adequate data are available at the scale of the gauged watersheds. Figure 10 compares the values of base flow index calculated for the selection of 960 stream flow gauges in Ontario and the Great Lake states using the PART (Rutledge 1998) and UKIH methods of hydrograph separation. The majority of the values calculated using the PART method are greater than the values calculated using the UKIH method and there is considerable scatter in the differences among the two methods. The average of the differences between the two sets of values is 0.15 and is significant when measured relative to the differences in the estimates of base flow index for the sub-basins of the Great Lakes, which is on the order of 0.1.

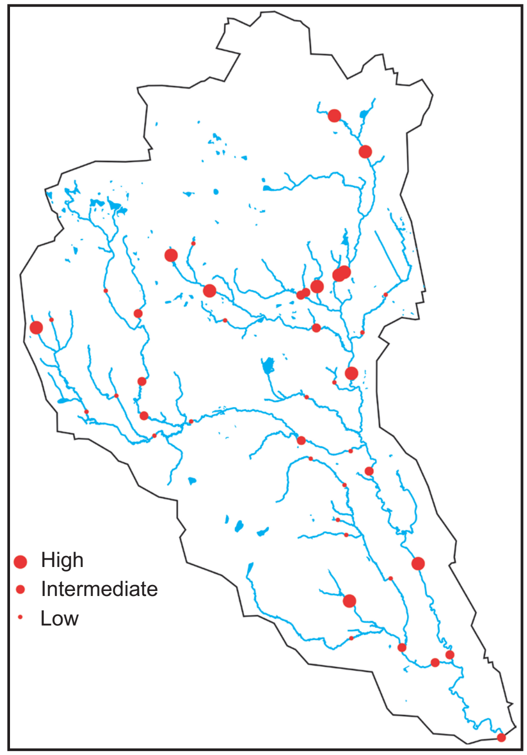

Figure 9. Distribution of the standardized values of low flow within the watershed of Duffins Creek above Pickering.

Source: Environment Canada and the U.S. Geological Survey, Geological Survey of Canada, and Ontario Ministry of Natural Resources

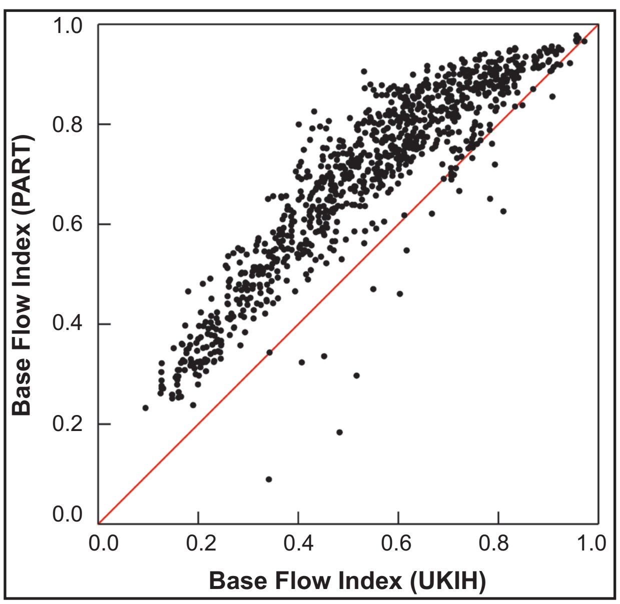

Figure 10. Comparison of the values of base flow index calculated using the PART method of hydrograph separation to the values calculated using the UKIH method.

Source: Environment Canada and the U.S. Geological Survey

Pressures

The discharge of groundwater to surface water features is the end-point of the process of groundwater recharge, flow, and discharge. Human activities impact groundwater discharge by modifying the components of this process where the time, scale, and to some extent the severity, of these impacts is a function of hydrogeological factors and the proximity of surface water features. Increasing the extent of impervious surfaces during residential and commercial development and installation of drainage to increase agricultural productivity are examples of activities that may reduce groundwater recharge and ultimately groundwater discharge. Withdrawals of groundwater as a water supply and during dewatering (pumping groundwater to lower the water table during construction, mining, etc.) remove groundwater from the flow regime and may also reduce groundwater discharge. Groundwater discharge may be impacted by activities such as the channelization of water courses that restrict the motion of groundwater across the groundwater and surface water interface. Human activities also have the capacity to intentionally, or unintentionally, increase groundwater discharge. Induced storm water infiltration, conveyance losses within municipal water and wastewater systems, and closure of local water supplies derived from groundwater are examples of factors that may increase groundwater discharge. Climate variability and change may compound the implications of human activities relative to groundwater recharge, flow, and discharge.

Management Implications

Groundwater has important societal and ecological functions across the Great Lakes basin. Groundwater is typically a high quality water supply that is used by a significant portion of the population, particularly in rural areas where it is often the only available source of water. Groundwater discharge to rivers, lakes, and wetlands is also critical to aquatic species and habitat and to in-stream water quantity and quality. These functions are concurrent and occasionally conflicting. Pressures such as urban development and water use, in combination with the potential for climate impacts and further contamination of the resource, may increase the frequency and severity of these conflicts. In the absence of systematic accounting of groundwater supplies, use, and dependencies, it is the ecological function of groundwater that is most likely to be compromised.

Managing the water quality of the Great Lakes requires an understanding of water quantity and quality within the inland portion of the basin, and this understanding requires recognition of the relative contributions of surface runoff and groundwater discharge to stream flow. The results described in this report indicate the significant contribution of groundwater discharge to flow within the tributaries of the Great Lakes. The extent of this contribution has tangible management implications. There is considerable variability in groundwater recharge, flow, and discharge that must be reflected in the land and water management practices that are applied across the basin. The dynamics of groundwater flow and transport are different than those of surface water flow. Groundwater discharge responds more slowly to climate and maintains stream flow during periods of reduced water availability, but this capacity is known to be both variable and finite. Contaminants that are transported by groundwater may be in contact with geologic materials for years, decades, and perhaps even centuries or millennia. As a result, there may be considerable opportunity for attenuation of contamination prior to discharge. However, the lengthy residence times of groundwater flow also limit opportunities for the removal of contaminants, in general, and non-point source contaminants, in particular.

Comments from the author(s)

The indicated status and trend are estimates that the authors consider to be a broadly held opinion of water resource specialists within the Great Lakes basin. Further research and analysis is required to confirm these estimates and to determine conditions on a lake by lake basis.

Acknowledgments

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Sources

Base flow information cited in the report is a product of the study, *Groundwater and the Great Lakes: A Coordinated Binational Basin-wide Assessment in Support of Annex 2001 Decision Making*, conducted by the U.S. Geological Survey in cooperation with Environment Canada's National Water Research Institute and the Great Lakes Protection Fund. Data are published in Neff *et al.* (2005), cited below.

Citations

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